The International EnKF Workshop 2022
02 June, Thursday, 2022. Balestrand, Norway.

Gas production from methane hydrates and application of data assimilation technique

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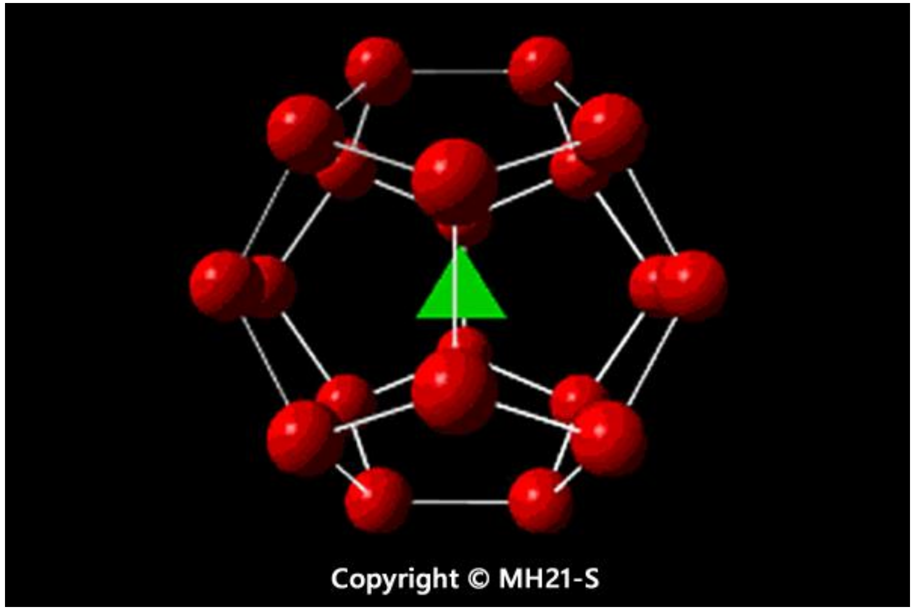
Today's talk

- Gas production from naturally occurring gas hydrate in reservoirs
  - What is methane hydrate?
  - Gas production technology and process of gas hydrate dissociation
  - Why we are interested in data assimilation and gas hydrate specific agenda
  - Long-term gas production test plan in Alaska
- Preliminary Data Assimilation Tests
  - Introduction
    - Simulator (MH21-HYDRES) & DA Framework (PDAF)
    - Data Assimilation algorithm
    - Observation Data
    - Simulation model
  - Preliminary Data Assimilation Test (2D model)
    - Case1
    - Case2
  - Future Study Plan (3D model)



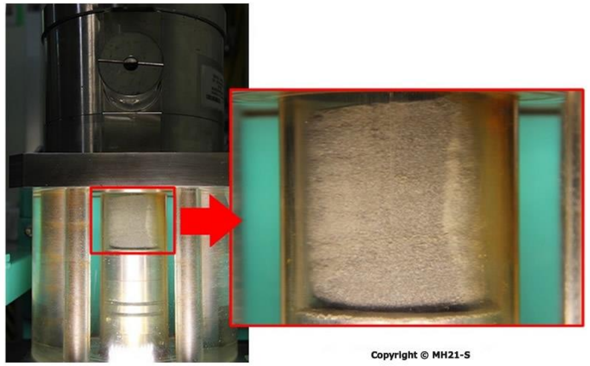
Gas production from naturally occurring gas hydrate in reservoirs

What is methane hydrates?

- **Solid material containing water and methane molecules**
- **Stable under high pressure and low temperature condition (> 2.7 MPa @ 0°C)**
- Huge abundance in deep-water subsea sediments or under permafrost regions
- Possible alternative natural gas resource if economically producible

←Combustion of artificial methane hydrate crystal

→ Gas hydrate-bearing natural sediment in transparent pressure cell



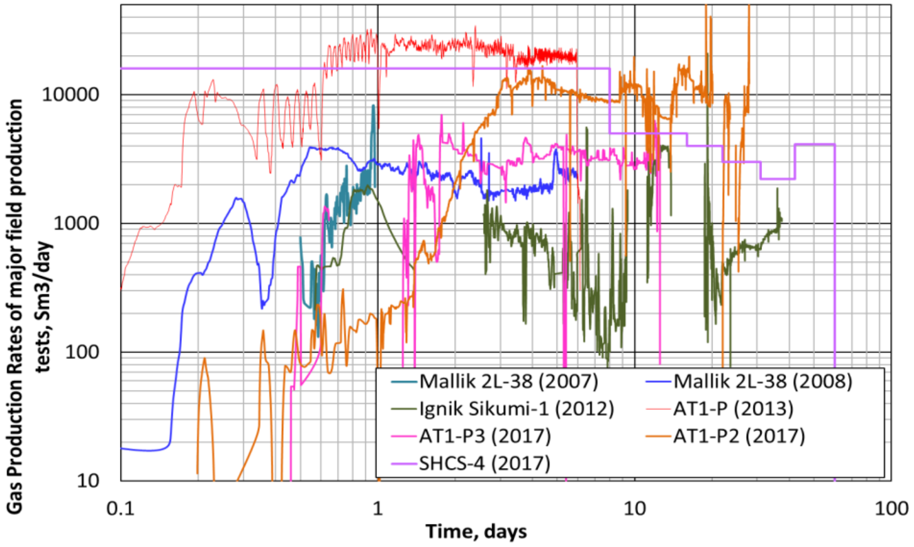
How to produce gas?

- Depressurization and thermal stimulation are possible solutions.
- **Depressurization method should be the most realistic** solution based on energy efficiency.

⇐ Methane hydrate dissociation is **endothermic process**

- Some gas production attempts have been conducted in Japan, China, Canada, US. (max. a few month)
- Long-term gas production behavior is still uncertain → **Necessity of long-term production test**

⇐ **Uncertainty of reservoir characters**



Gas production test results

Thermo-Chemo-Hydro coupled gas production processes by depressurization

Gas/liquid production from borehole:

$$Q_i = n\Big|_{borehole} \cdot \left[\frac{\rho_i k_{eff}^{(i)}}{\mu}\nabla p\right]$$

Darcy's low and mass conservation:

$$\frac{d(\rho_i S_i)}{dt} = \dot{m}_i + \nabla\cdot(\rho_i q_i),\ \ q_i = \frac{\rho_i k_{eff}^{(i)}}{\mu}\nabla p$$

Alternation of effective permeability:

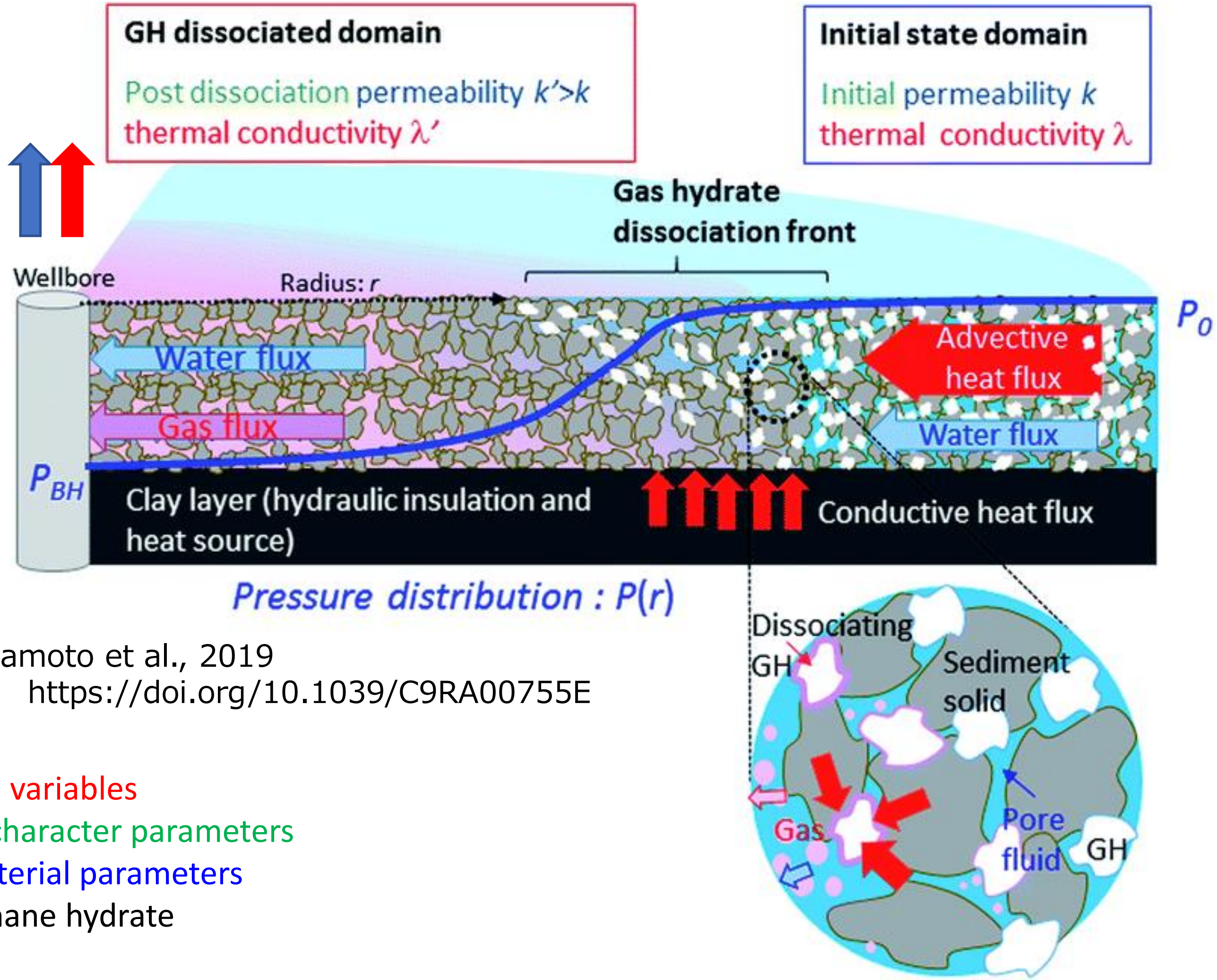
$$k_{eff}^{(i)} = k_{int}^{(i)}\left(1-\frac{S_h}{\phi}\right)^n k_r^{(i)}\left(\frac{S_i}{\phi}\right),$$

Fourier's law and Energy conservation:

$$\frac{d\left[T\sum_i(c_i\rho_i S_i)\right]}{dt} = H\frac{d\dot{m}_h}{dt} + \nabla\left[qT + \lambda_{eff}(\lambda_{int}, S_h)\nabla T\right]$$

Rate equation by Kim and Bishinoi :

$$\dot{m}_h = cA_h(p_{eq} - p)$$



Yamamoto et al., 2019
DOI https://doi.org/10.1039/C9RA00755E

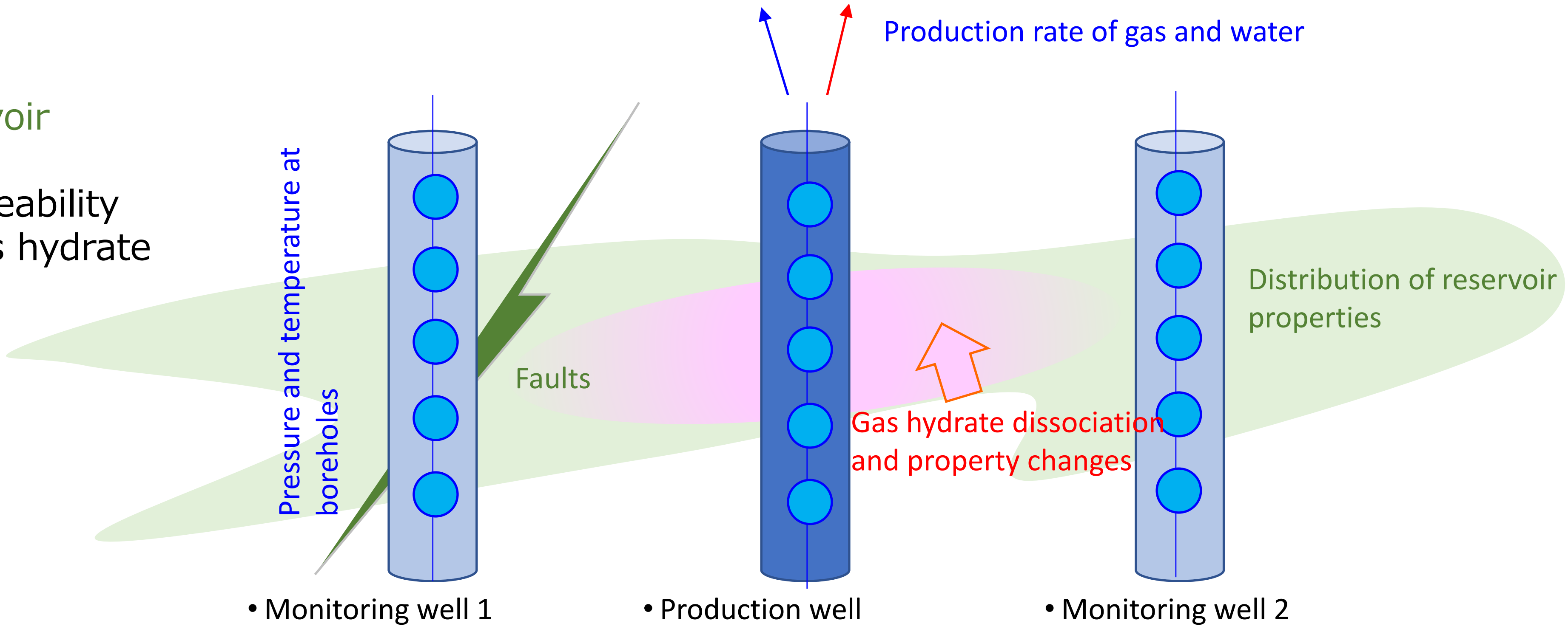
Red: independent variables
Green: reservoir character parameters
Blue: Variable material parameters
i: gas/water/methane hydrate

Distributions of thermal and hydraulic characters are key factors to govern the gas production, but lots of uncertainty

Data obtained during gas production test

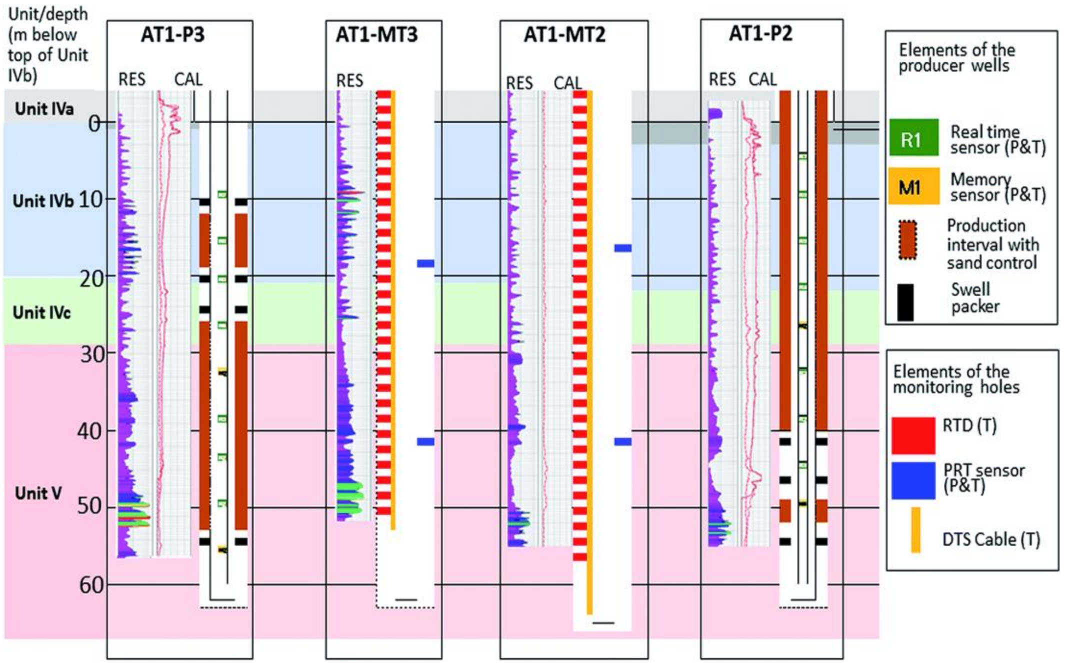
- Obtained data have been used to constrain reservoir character data through numerical history matching.
  - Seismic/log/core data for initial reservoir character data; permeability $\boldsymbol{k}$, gas hydrate saturation $\boldsymbol{S_h}$ etc.
  - Gas/water rates from producer wells; $\boldsymbol{Q_g}$, $\boldsymbol{Q_w}$
  - Pressure and temperature data in borehole; $\boldsymbol{P}$, $\boldsymbol{T}$
- For future long-term production tests, **Data Assimilation** can be a promising technique to improve precision/accuracy of production test.

- Alternation of reservoir character during the operation e.g. permeability improvement by gas hydrate dissociation)

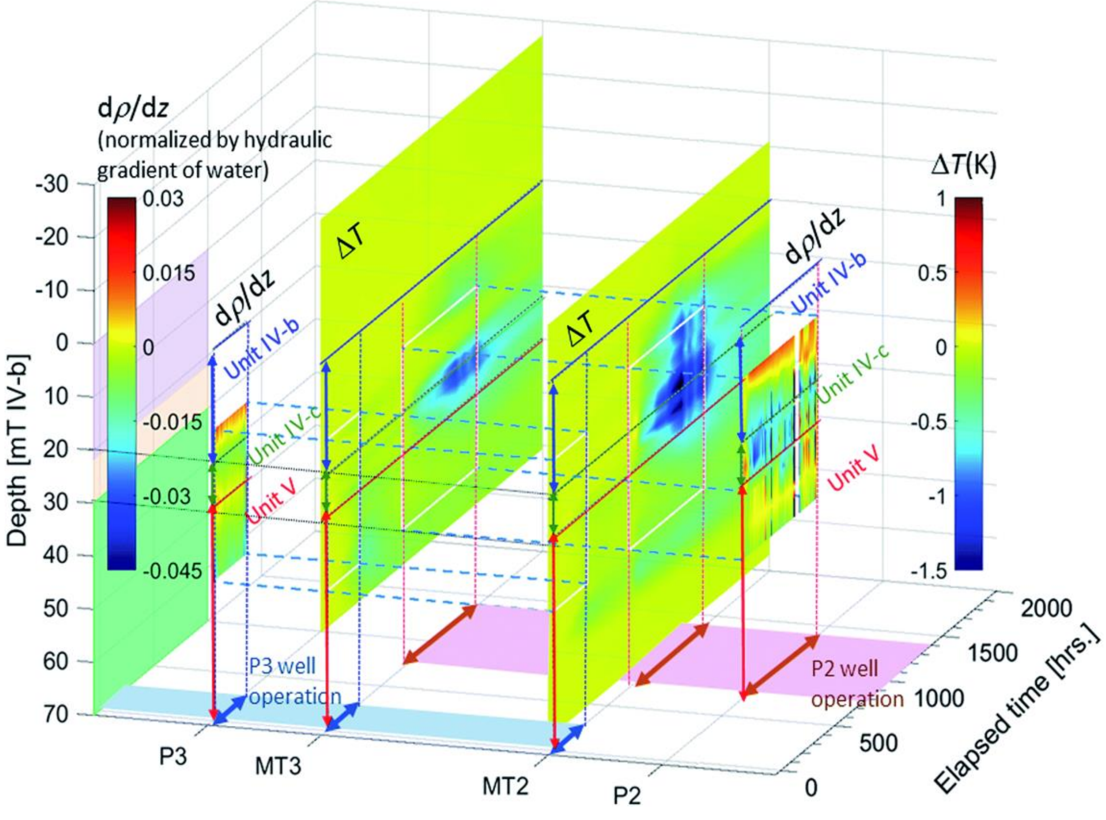


Data obtained during gas production test (2017 Nankai Trough)

- Obtained data have been used to constrain reservoir character data through numerical history matching.
    - Seismic/log/core data for initial reservoir character data; permeability ***k***, gas hydrate saturation $\boldsymbol{S_h}$ etc.
    - Gas/water rates from producer wells; $\boldsymbol{Q_g}$, $\boldsymbol{Q_w}$
    - Pressure and temperature data in borehole; ***P, T***
- For future long-term production tests, **Data Assimilation** can be a promising technique to improve precision/accuracy of production test.



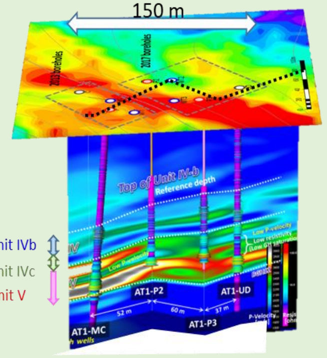
Pressure and temperature sensors in boreholes (producer x2 + observer x2)



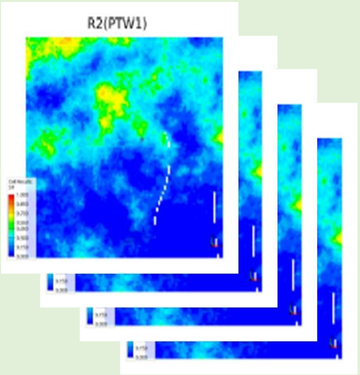
Obtained temperature data in each hole

Process of the assimilation

Initial reservoir model ensemble



Seismic, log and core data



Initial ensemble of reservoir model

Numerical simulation

$$\frac{d(\rho_i S_i)}{dt} = \dot{m}_i + \nabla p,$$

$$\frac{d(\rho_i S_i)}{dt} = \dot{m}_i + \nabla\cdot(\rho_i q_i),\ \ q_i = \frac{\rho_i k_{eff}^{(i)}}{\mu}\nabla p$$

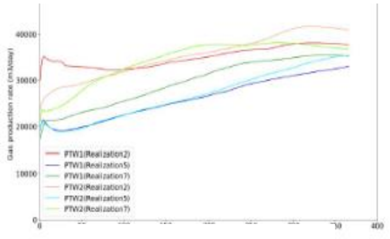
$$k_{eff}^{(i)} = k_{int}^{(i)}\left(1-\frac{S_h}{\phi}\right)^n k_r^{(i)}\left(\frac{S_i}{\phi}\right),$$

$$\frac{d\left[T\sum_i(c_i\rho_i S_i)\right]}{dt} = H\frac{d\dot{m}_h}{dt} + \nabla\left[qT + \lambda_{eff}(\lambda_{int}, S_h)\nabla T\right]$$

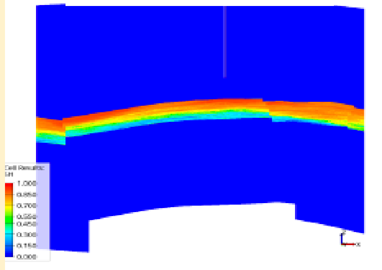
$$\dot{m}_h = cA_h(p_{eq} - p)$$

State variables:
Dynamic/static/quasi-static

Gas/water rates Q_g/Q_w



GH saturation S_H



THC simulation: physically consistent prediction of the next time step

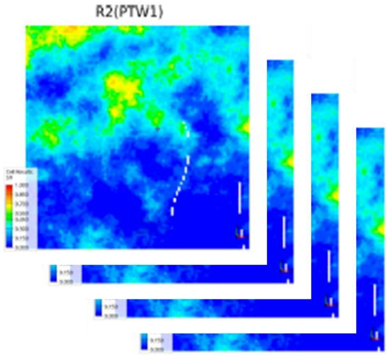
EnKF/EnS

$$\mathbf{y}^u_{k,j} = \mathbf{y}^p_{k,j} + \mathbf{K}_k(\mathbf{d}_{obs,k,j} - \mathbf{H}\mathbf{y}^p_{k,j}).$$

Update of state variables using Kalman filter

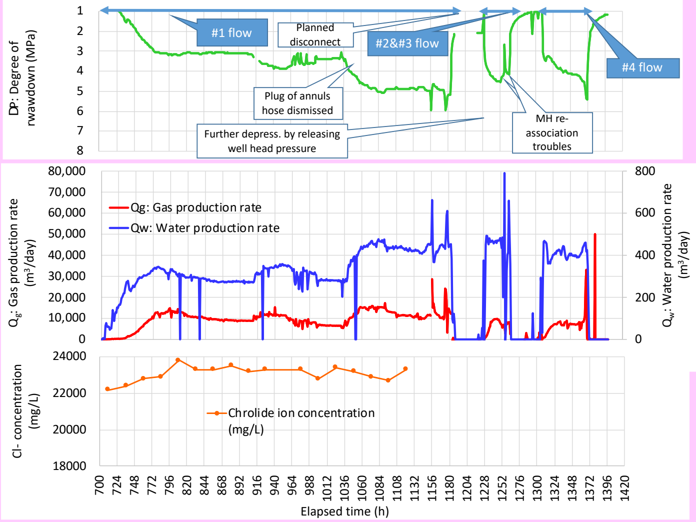
$$\mathbf{K}^{\Psi} = \mathbf{C}^{\Psi}_{b}\mathbf{H}_L(\mathbf{H}\mathbf{C}^{\Psi}_{b}\mathbf{H}_L + \mathbf{C}^{D})_{-1}$$

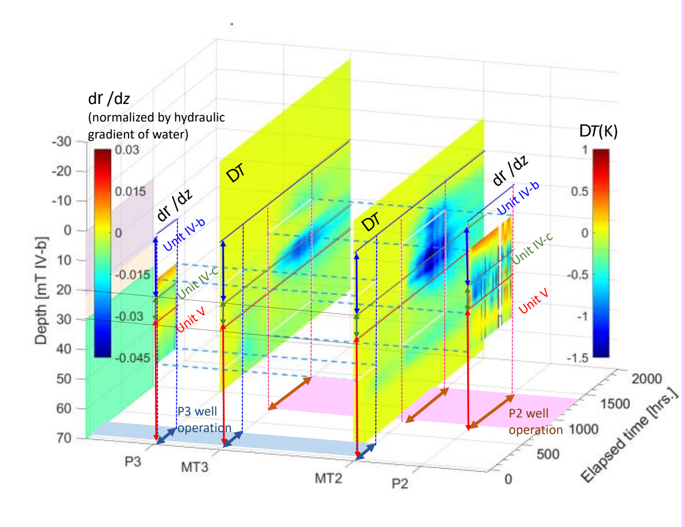
$$\mathbf{C}^p_{\Psi,k}\mathbf{H}^T = \frac{1}{N_e-1}\sum_{i,j=1}^{N_e}(\mathbf{y}^p_{k,i}-\overline{\mathbf{y}}^p_k)(\mathbf{y}^p_{k,j}-\overline{\mathbf{H}\mathbf{y}^p_k})^T,$$



Updated ensemble of state variables
(state variable of t_n to t_{n+1})

Actual measurements of gas/water rates and P/T each time step

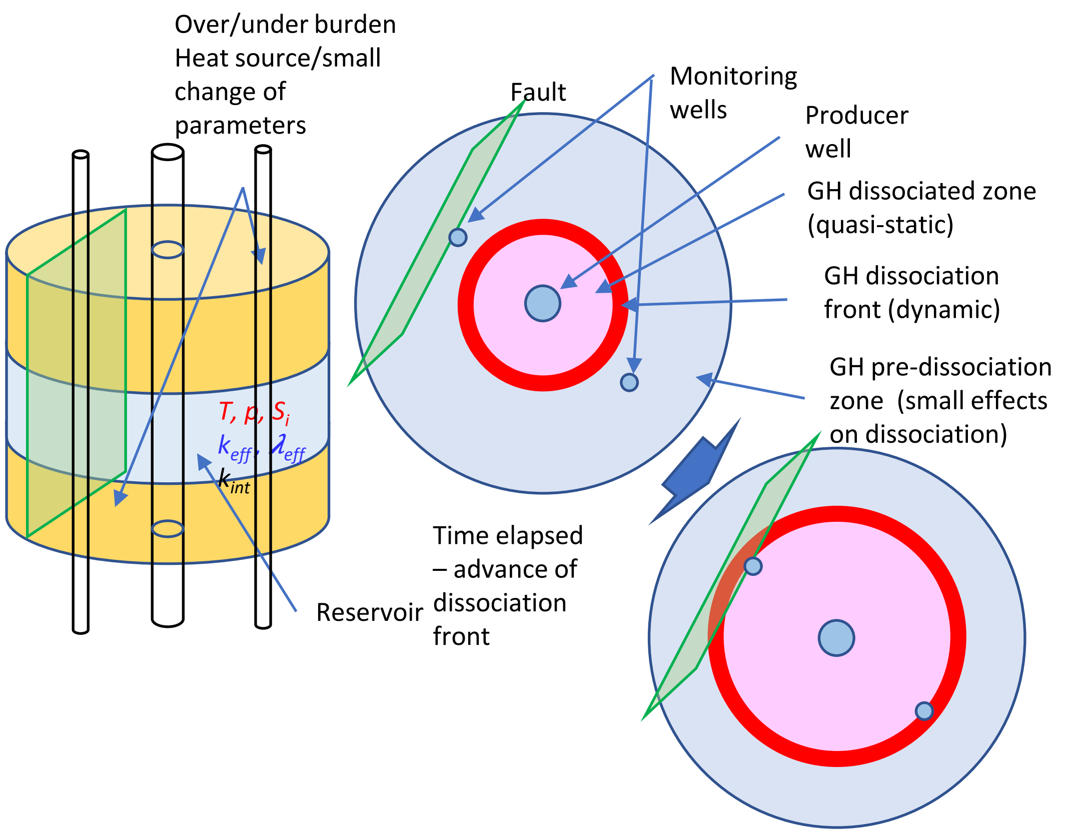




Methane hydrate specific features

- THC coupling – more variables than usual reservoir modeling
  - Pressure + **Temperature**
  - Two phase flow (gas and water)
  - **Phase change** between solid and gas/liquid
- Expansion of GH dissociation front
  - **Actual reaction zone is limited**
- **Strong correlation between variables**
  - Effective permeability ↔ GH saturation
  - Pressure drop ↔ Temperature drop ↔ GH saturation change
- Temperature data corresponding to GH dissociation
- Challenges
  - Further number of variables
    - Dynamic: Q_g, Q_w, P, T, S_h,
    - Static/conventional k_{int}, $k_{rg}(S_g)$, $k_{rw}(S_w)$
    - Gas hydrate saturation dependent quasi-static:
      - Effective permeability, heat capacity and thermal conductivity:

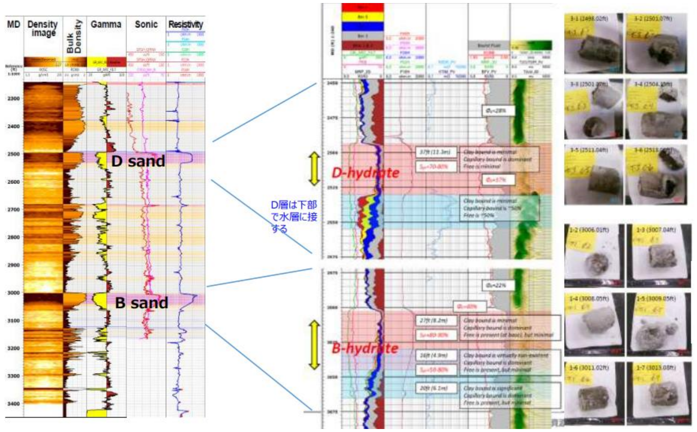
        $k_{eff}(S_h)$, $C(S_h)$, $\lambda_{eff}(S_h)$



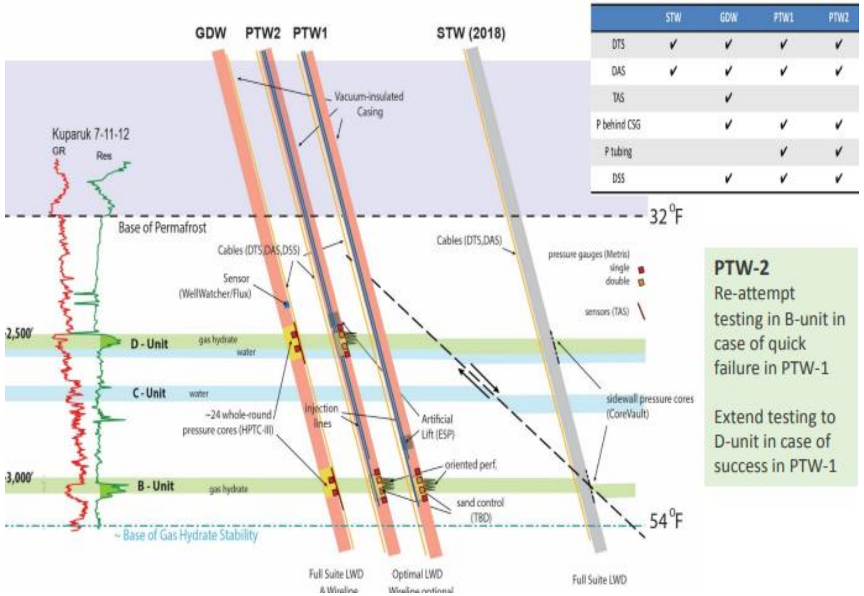
Long-term production trial: Plan of Alaska Production Test

Japan-US collaboration project planned to start next winter

- Geological settings
  - A site in Prude Bay Unit of Alaska North Slope
  - Two GH-bearing zones have been identified
  - Existence of vertical/lateral heterogeneity and faults in vicinity of the test location
- Operation and monitoring plan
  - Max. one-year long gas production by depressurization
  - Two producer holes – one by one operation
    - GH dissociation by depressurization method
    - Several months continuous flow
  - Two monitoring holes
  - PT measurements in all holes
- Points of interest
  - Risk of development of skin
  - Excess water production from water-bearing zone
  - Free gas production from deeper zone
  - Effects of existing faults



Occurrence of gas hydrate in upper (D) and lower (B) zones seen in log and core samples (METI, 2019
https://www.meti.go.jp/shingikai/energy_environment/methane_hydrate/pdf/036_04_00.pdf



Boswell, 2020,
https://www.energy.gov/sites/prod/files/2020/12/f81/Alaska%20Project%20Update.pdf

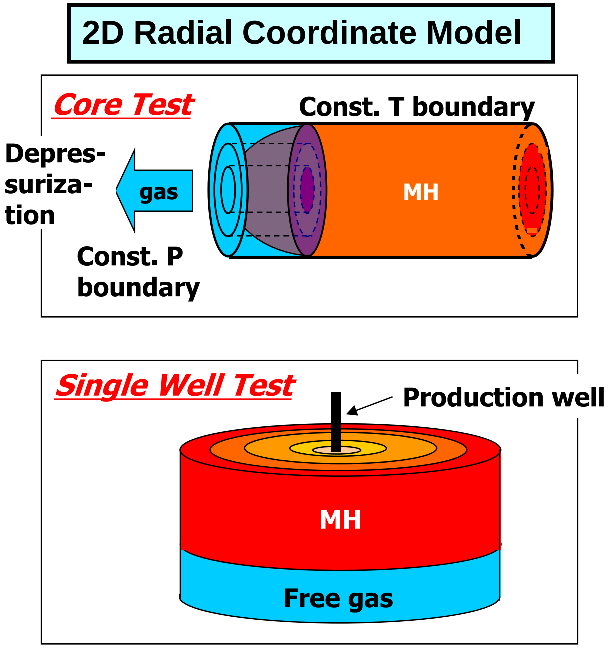
Preliminary Data Assimilation Tests

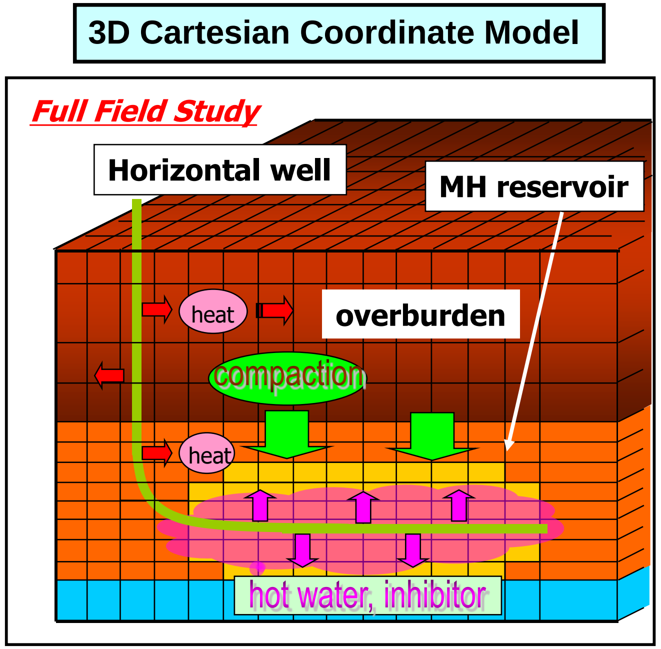
Introduction

Simulator & Data Assimilation Framework

◆ **Simulator:** MH21-HYDRES

THC(Thermo-Hydro-Chemical) and multiphase reservoir simulator developed for gas hydrate production simulation by JOE and AIST .



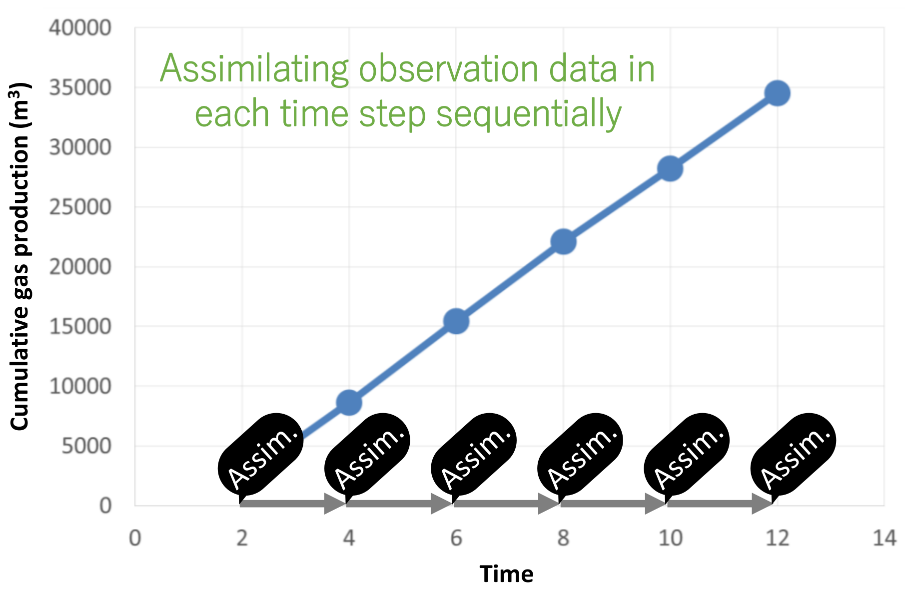


◆ **Data Assimilation Framework:** PDAF

The Parallel Data Assimilation Framework developed by Computing Center of the Alfred Wegener Institute.

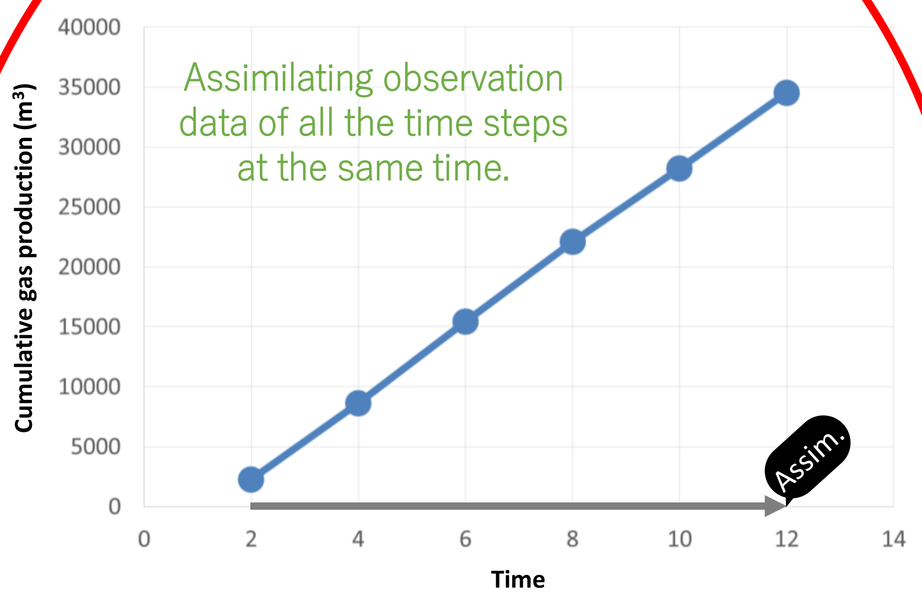
Data Assimilation Algorithm

Filter



- Allow to modify physical parameters discontinuously
  - ➡ Considered to be suitable for highly nonlinear system
- However, discontinuous physical parameter changes caused by DA could lead to catastrophic calculation instability in MH simulations

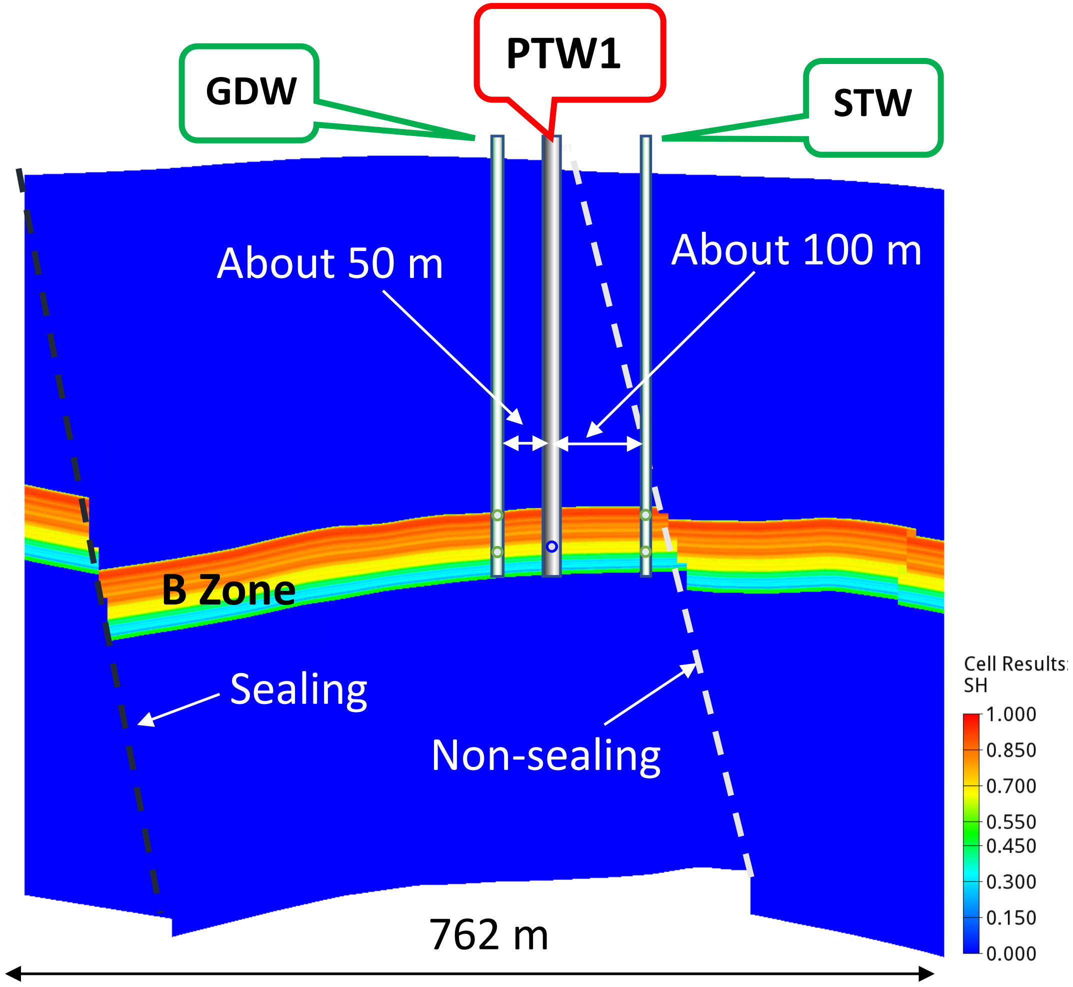
Smoother



- Modifying parameters at the initial condition so as to match observation data of all the time steps
  - ➡ Relatively difficult to follow sudden physical condition changes than filter
- However, calculation instabilities caused by discontinuous physical parameter modification never happen.
- In addition, iteratively application of smoother method (such as iterative ES or ES-MDA) could improve the accuracy of DA.

Observation Data

Producer＋Two observation wells



Producer

- PTW1（Production Term: 1 year, Bottom-hole Flowing Pressure = 3 MPa const.）
  - ☐ Gas/Water Production Rates

Observation Wells

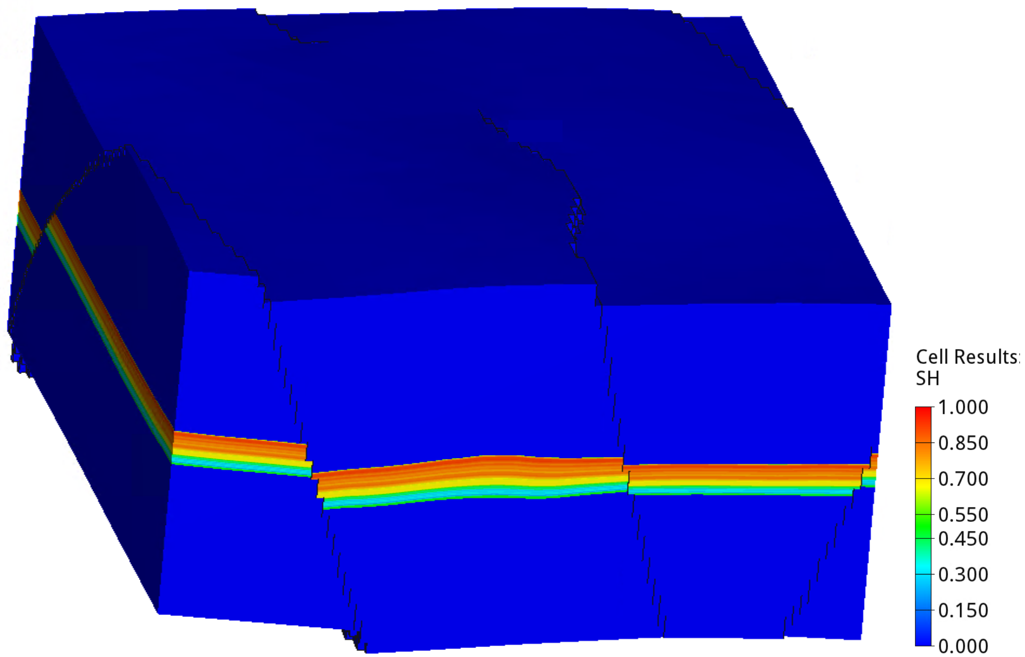
- GDW（located about 50 m west of PTW1）
- STW（located about 100 m east of PTW1）

☐ Reservoir Pressure
- Fixed point observation in B zone (2 points)

☐ Reservoir Temperature
- Along with the observation wells

Simulation Model

3D Model for the Long Term Production Test



- ✓ Fault/Layer Thickness Change
- ✓ Lateral Heterogeneity

But…,

- ✓ Number of Cells = 2.64 million (>= 5 million after applying LGR)
- ✓ Required Amount of Memory ≃ 20 GByte
- ✓ Calculation Time ≃ 5～10 days per case (1 year prediction)

⇩

Practically not applicable to the data assimilation where more than 100 ensemble members are required

Faster Model than 3D ➡ 2D Radial Model

However, 2D radial models have huge representation errors (unable to express fault/lateral heterogeneity, etc.) Are they really applicable to reservoir parameter estimation through DA?

➡ **Need to be evaluated**

Preliminary Data Assimilation Test (2D Model)

Preliminary Data Assimilation Test

- **Limited Observation Data (Producer + 2 observation wells)**
- **2D Radial Model (huge representation errors)**

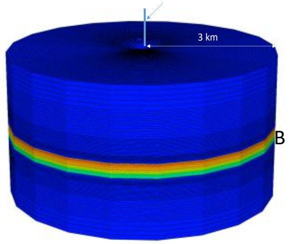
How accurately can reservoir parameters be estimated?

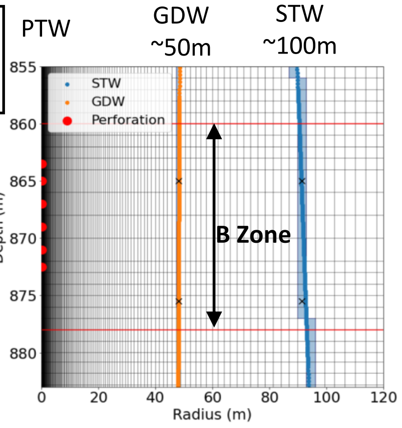
Preliminary Data Assimilation Tests by **2D Radial Model**

By **extracting hypothetical observation data** from the simulation results of the two different **reservoir models** (2D radial & 3D Homogeneous)

Case1 Reference: 2D Radial Model
(No Representation Error)

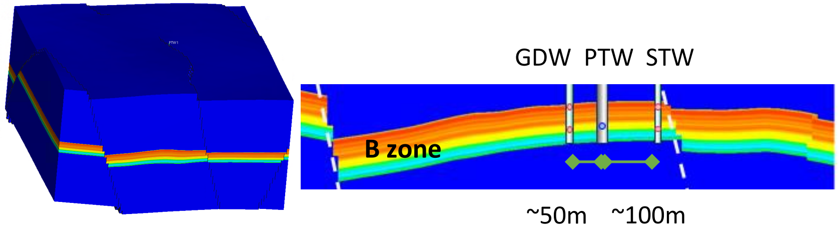
Extracting the following data
- Production Rates
- Pressure/Temperature





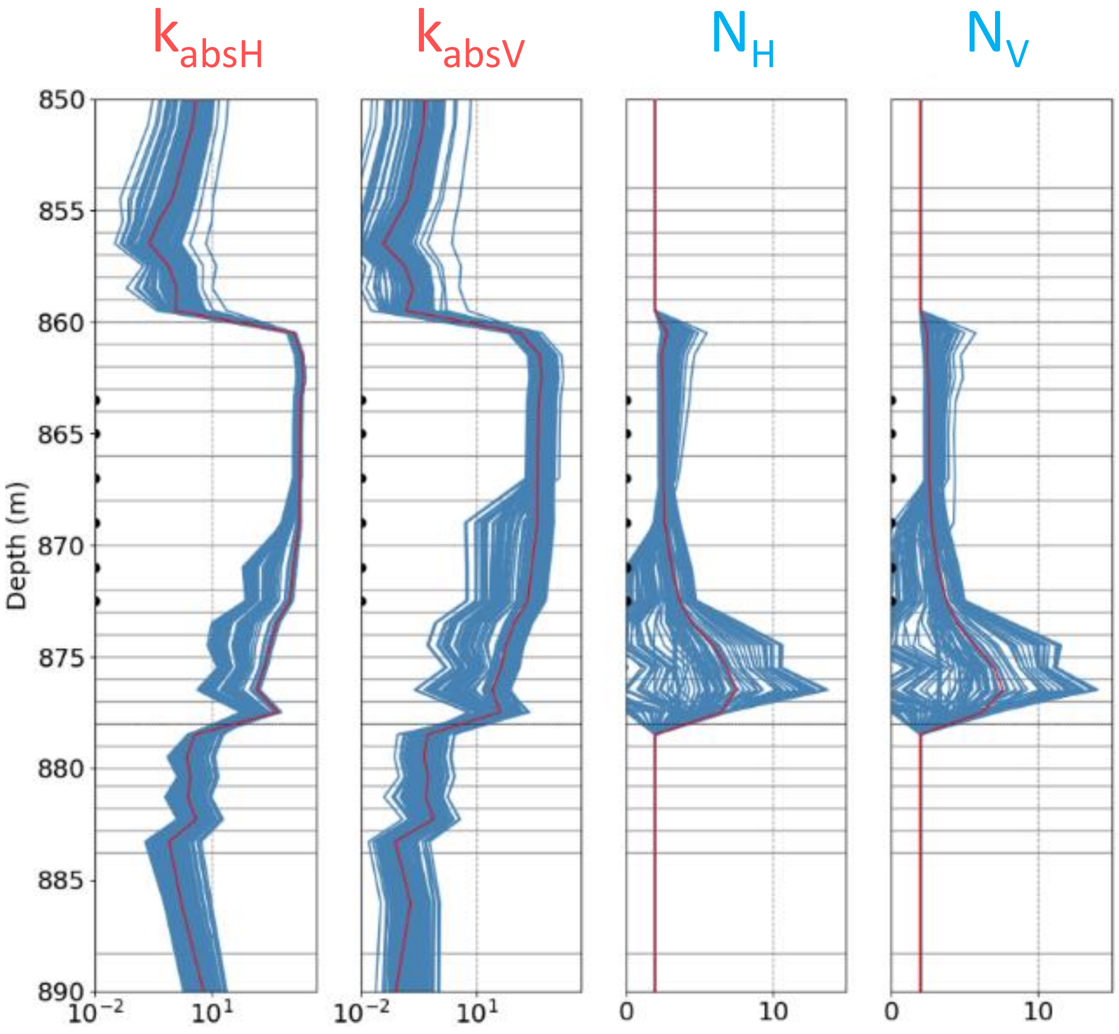
Case2 Reference: 3D Homogeneous Model
(Certain Degree of Representation Error)

Extracting the following data
- Production Rates
- Pressure/Temperature



Estimated **permeability** and **permeability reduction index** of each layer thorough DA using Ensemble Smoother

Initial Ensembles of the Estimated Parameters (permeability and permeability reduction index)



- Horizontal Absolute Permeability (k_{absH})
- Vertical Absolute Permeability (k_{absV})
- Horizontal Permeability Reduction Index (N_H)
- Vertical Permeability Reduction Index (N_V)

click

$$k_{eff} = k_{abs}(1 - S_H)^N$$

Well Log Interpretation Value

Case1

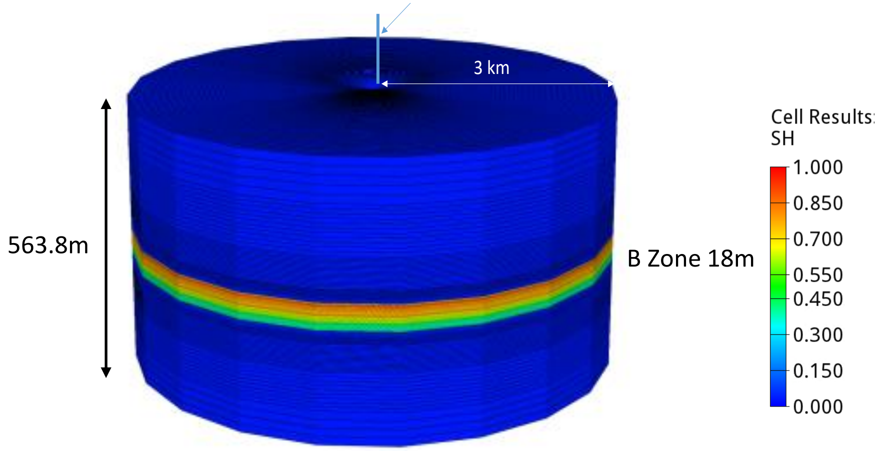
Observation Data: 2D Model

Data Assimilation: 2D Model

Case1 Settings for Data Assimilation

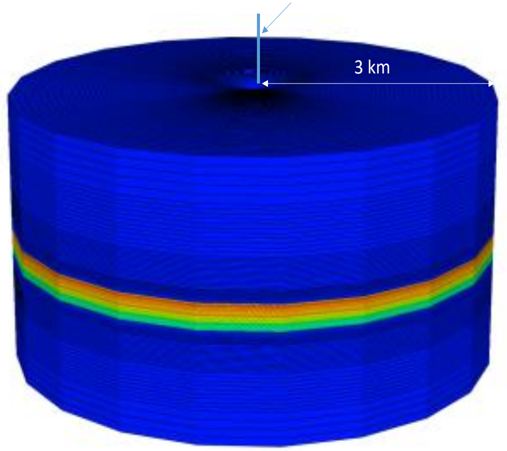
☐ Reference Model：2D Radial Model

(Most likely well-log interpretation model)

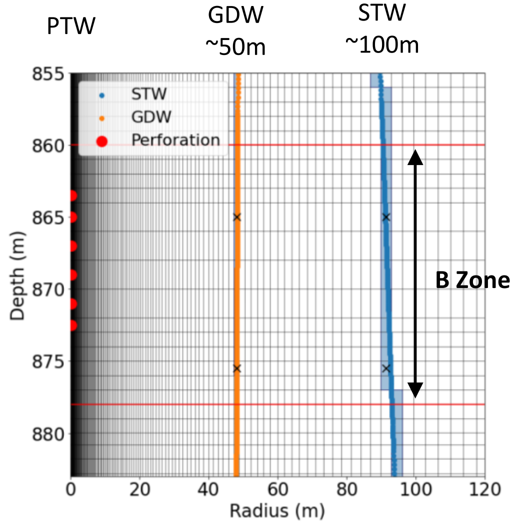


☐ Model for DA：2D Radial Model

(Grid Frame = Same as the Reference)



☐ Observation Data for DA, and Data Acquisition Timing

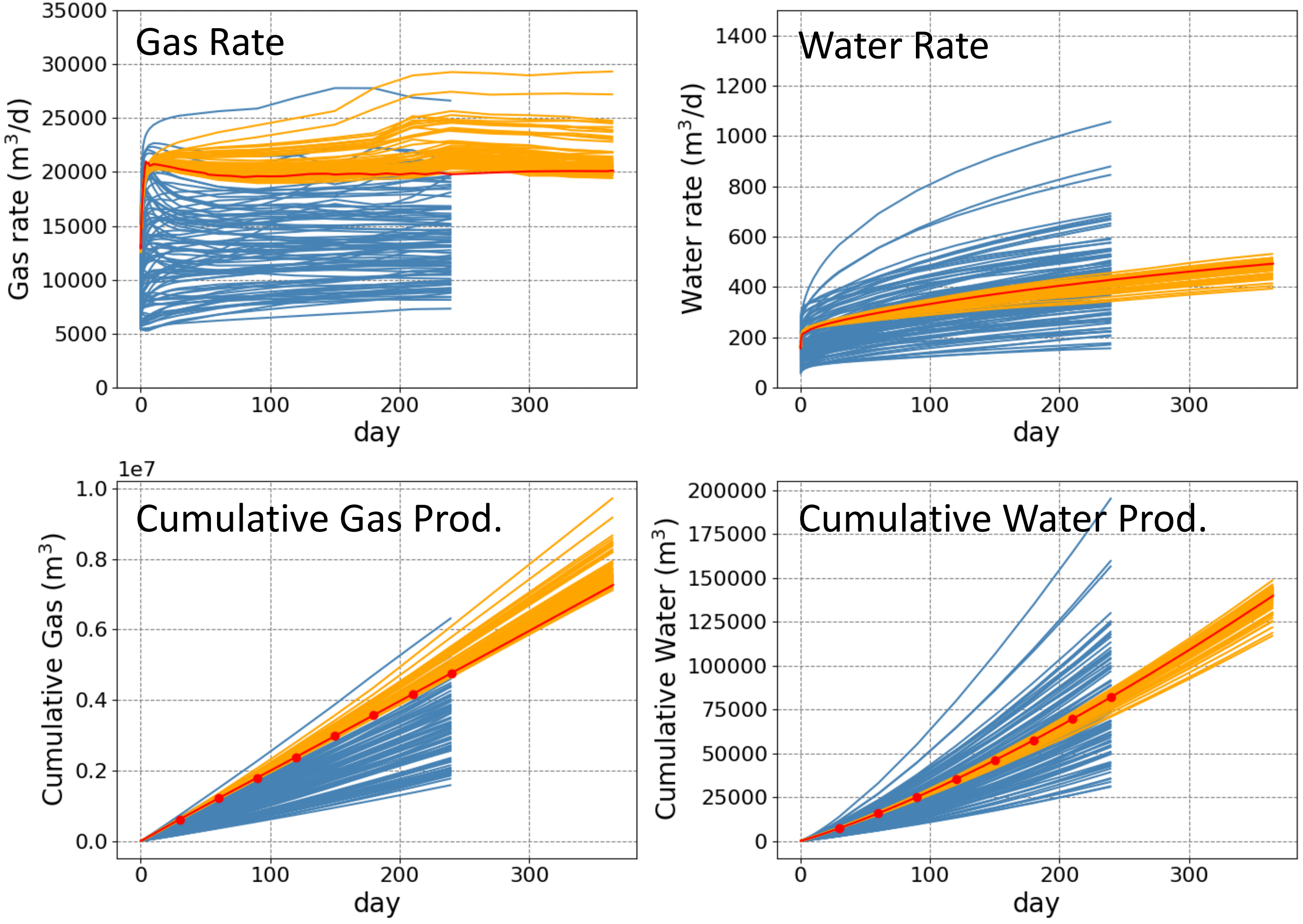


- **PTW1:** Cumulative Gas/Water Prod.
- **GDW:** Pressure/Temperature
- STW: Pressure/Temperature

☐ Data Acquisition Timing:

every 30 days until 240 days

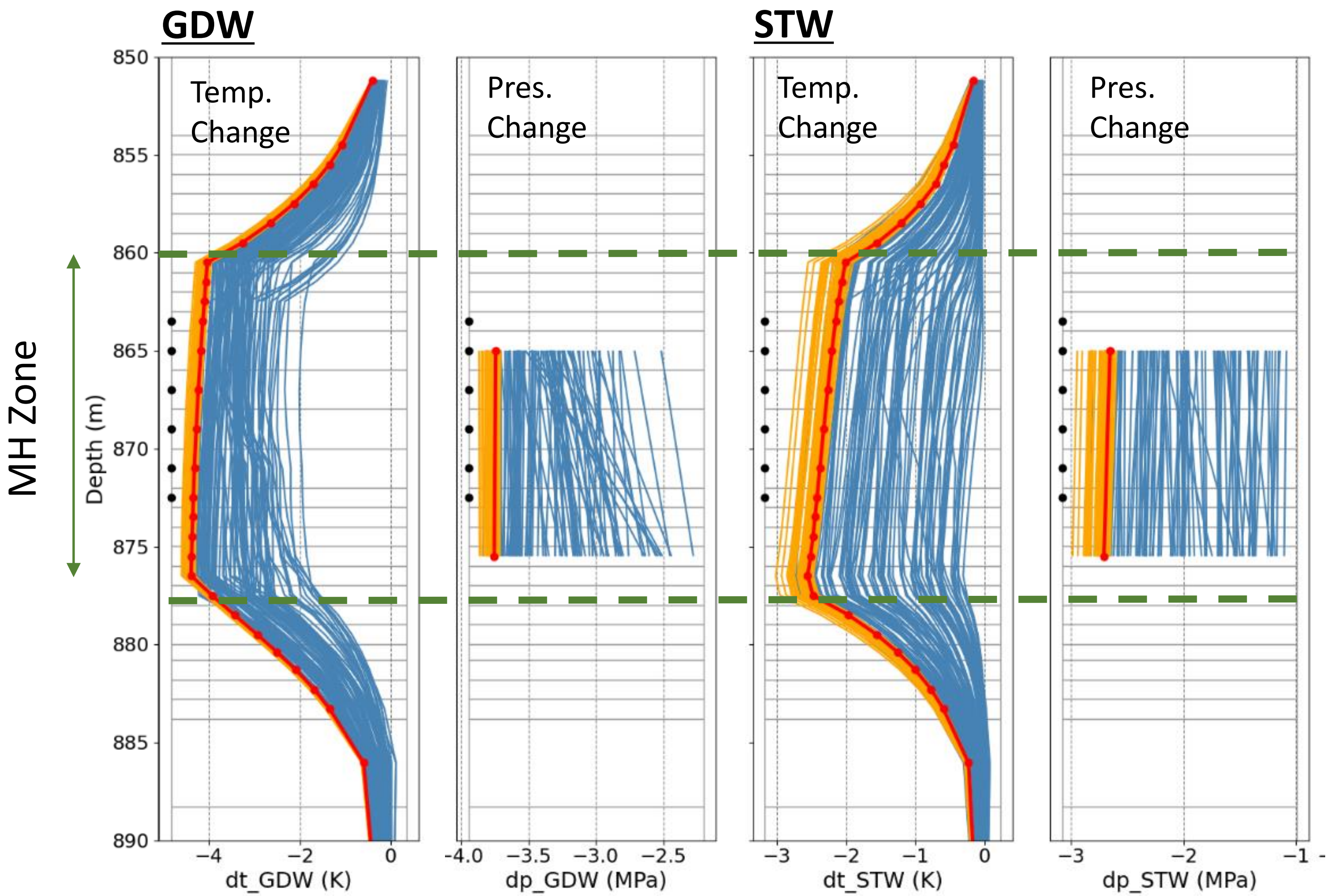
Case1 Results (Observation Data: PTW1)



Blue Lines: Initial Ensemble Results
Orange Lines: Assimilation Results
Red Lines: Reference Result

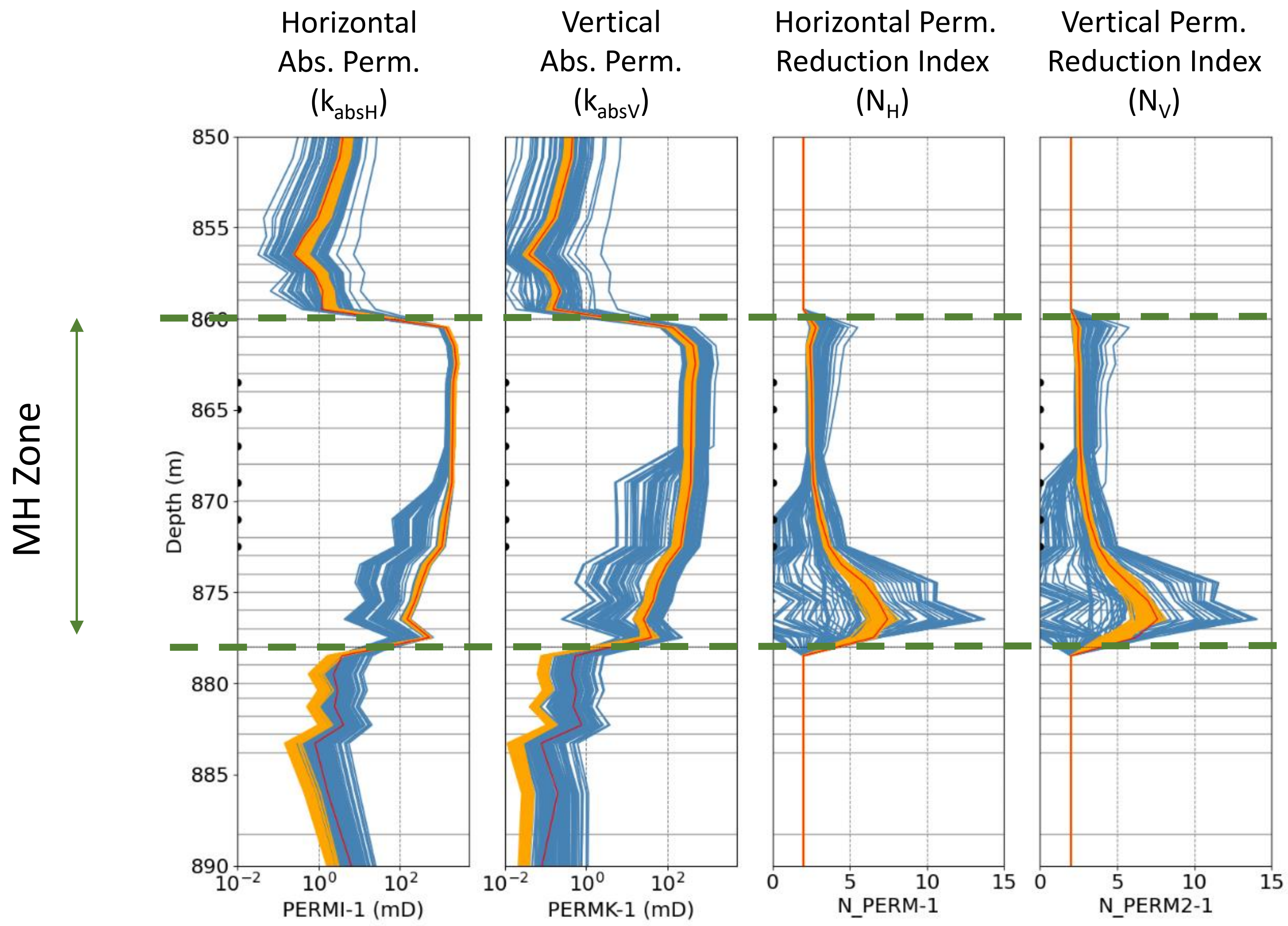
Case1 Results (Observation Data: GDW &STW)

Pres. & Temp. Distribution After 240 Days



Blue Lines: Initial Ensemble Results
Orange Lines: Assimilation Results
Red Lines: Reference Result

Case1 Results (Estimated Parameters)



Blue Lines: Initial Ensemble
Orange Lines: Assimilation Results
Red Lines: Reference

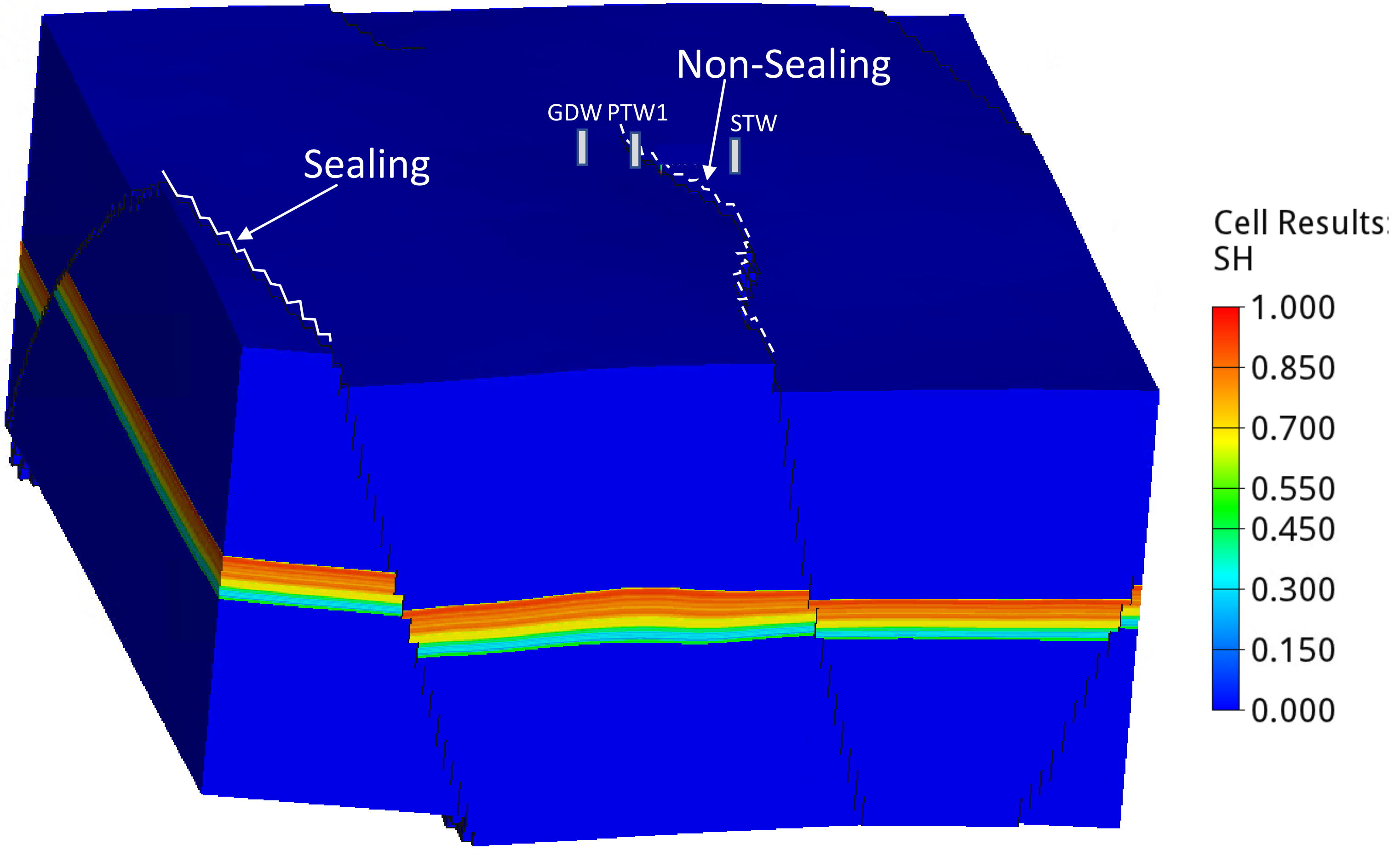
Case2

Observation Data: 3D Homogeneous Model

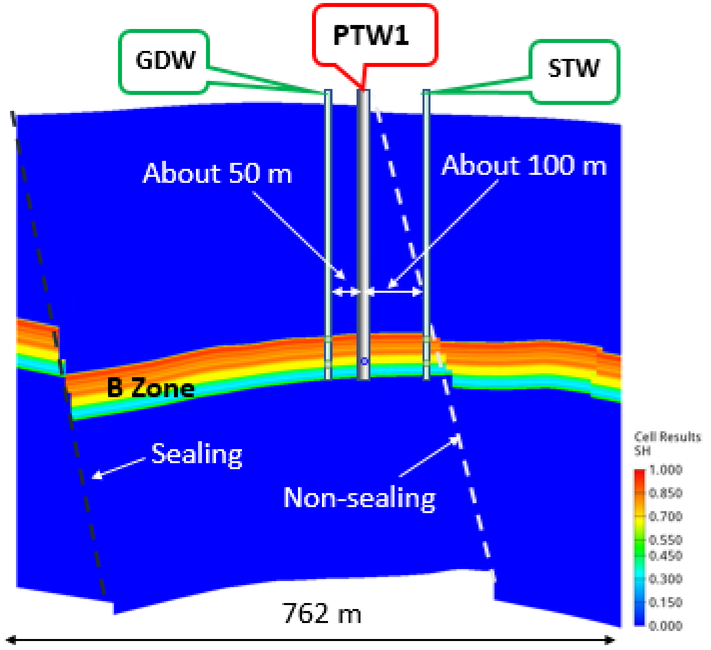
Data Assimilation: 2D Model

Reference Model for Hypothetical Observation Data:

3D Homogeneous Model
(most likely well-log interpretation model)



- **Observation Data for DA, and Data Acquisition Timing**

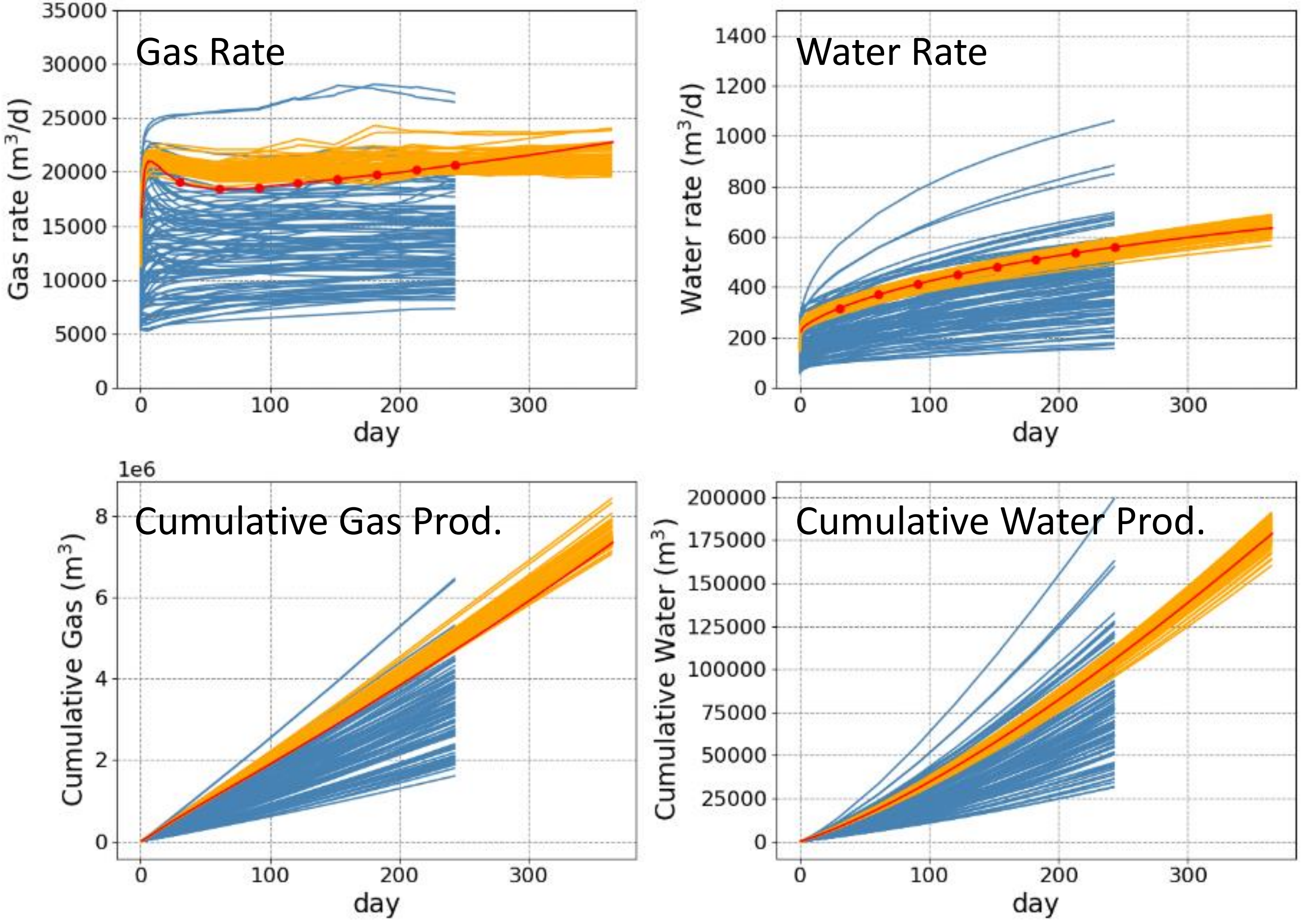


- **PTW1:** Cumulative Gas/Water Prod.
- **GDW:** Pressure/Temperature

STW data was not included in this Case

- **Data Acquisition Timing**: every 30 days until 240 days

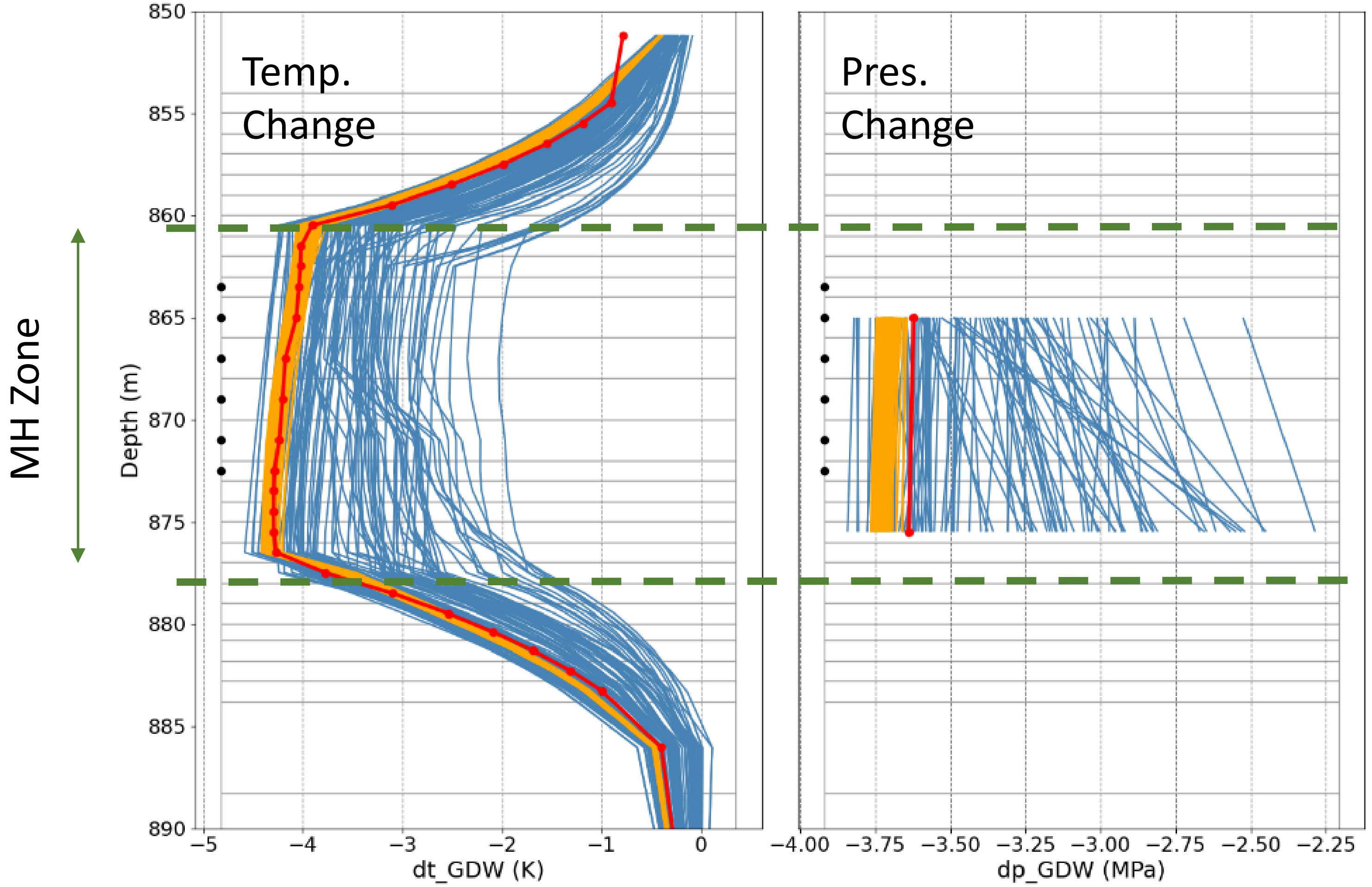
Case2 Results (Observation Data: PTW1)



Blue Lines: Initial Ensemble Results
Orange Lines: Assimilation Results
Red Lines: Reference Result

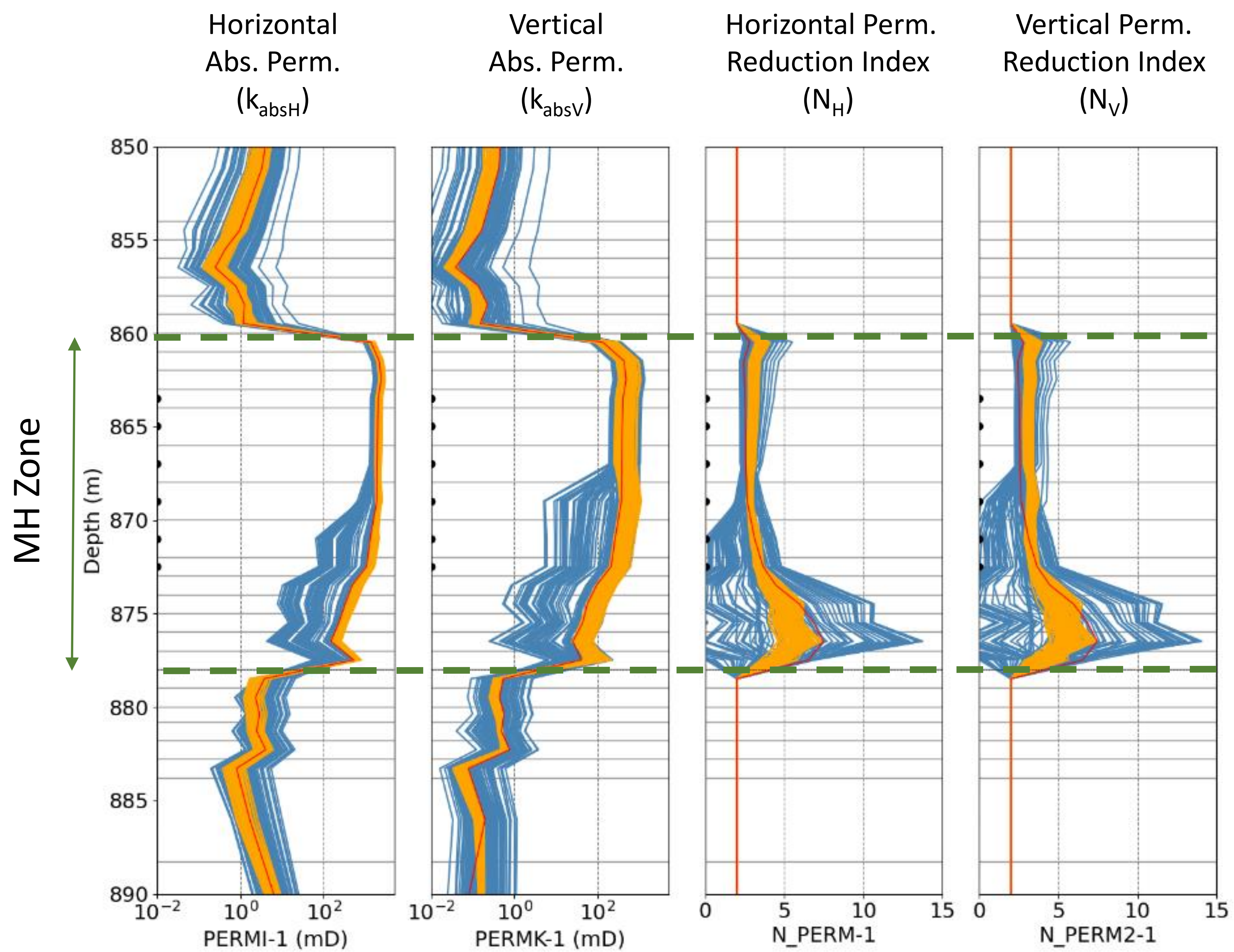
Case2 Results (Observation Data: GDW)

Data Assimilation Results After 240 Days



Blue Lines: Initial Ensemble Results
Orange Lines: Assimilation Results
Red Lines: Reference Result

Case2 Results (Estimated Parameters)



Blue Lines: Initial Ensemble
Orange Lines: Assimilation Results
Red Lines: Reference

Conclusion

◆We confirmed that the observation data taken from the two reference models could be well reproduced by the data assimilation of the 2D radial model, and reservoir properties of the reference models could be estimated with a certain degree of accuracy.

◆These results suggest that reservoir properties could be estimated with a certain degree of accuracy through data assimilation in the actual long term production test in Alaska.

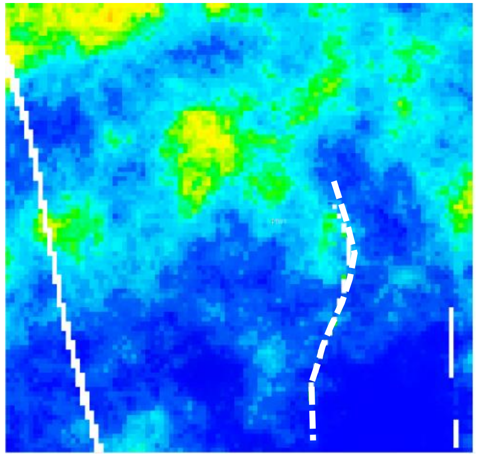
Future Study Plan
(3D Model)

Future Study Plan (3D Model)

Estimation of **Horizontal Heterogeneity of Reservoir Properties** & **Fault Transmissibility**

Reference Model:

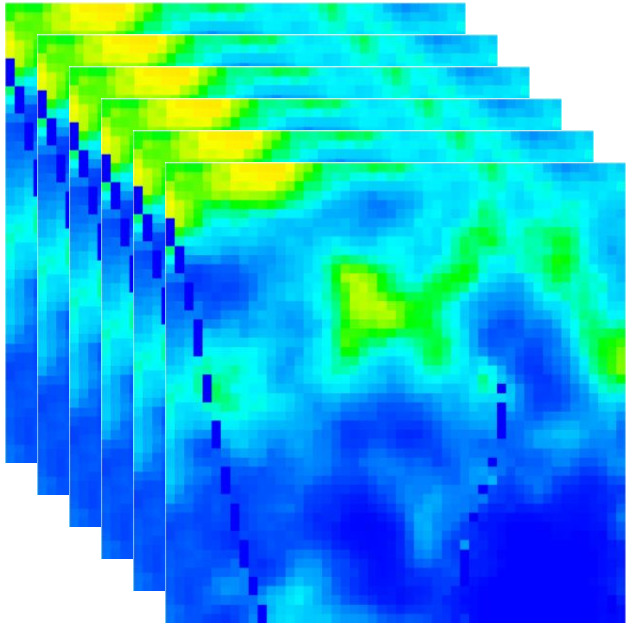
Fine 3D Model
(100*100*264)



Calc. Time:
about 5 days for 1 year prediction

Model for DA:

Upscaled 3D Model Ensembles
(50*50*41)



Calc. Time:
about 0.2 days for 1 year prediction

As a next step, planning to investigate how accurately the following properties of the reference 3D model could be estimated by DA of the upscaled 3D model.

- Horizontal Distribution of Representative Reservoir Properties (S_h, k_{abs}, etc.)
- Fault Transmissibility near the Production Well

If this system successfully works, data assimilation using the upscaled 3D model could be possible in the long term production test in Alaska.

Acknowledgements

- The project is a part of the MH21-S research program funded by Ministry of Economy, Trade and Industry (METI)

- Alaska long-term production test partners:
  - JOGMEC
  - National Energy Technology Laboratory (NETL)
  - The United State Geological Survey (USGS)

  Funded by METI and US Department of Energy (USDOE)

MH21-S partners and sponsor

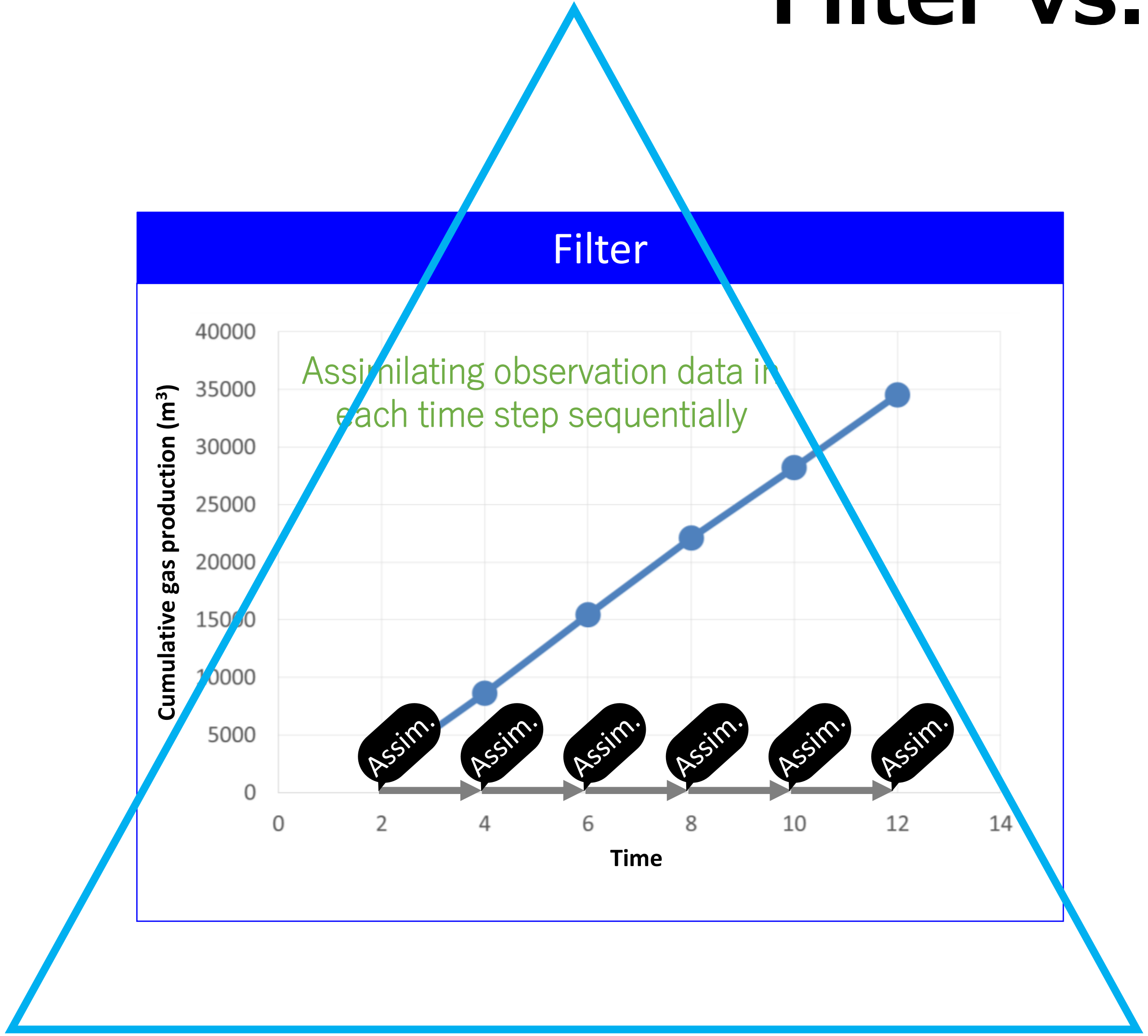
Alaska long-term production test partners and sponsor

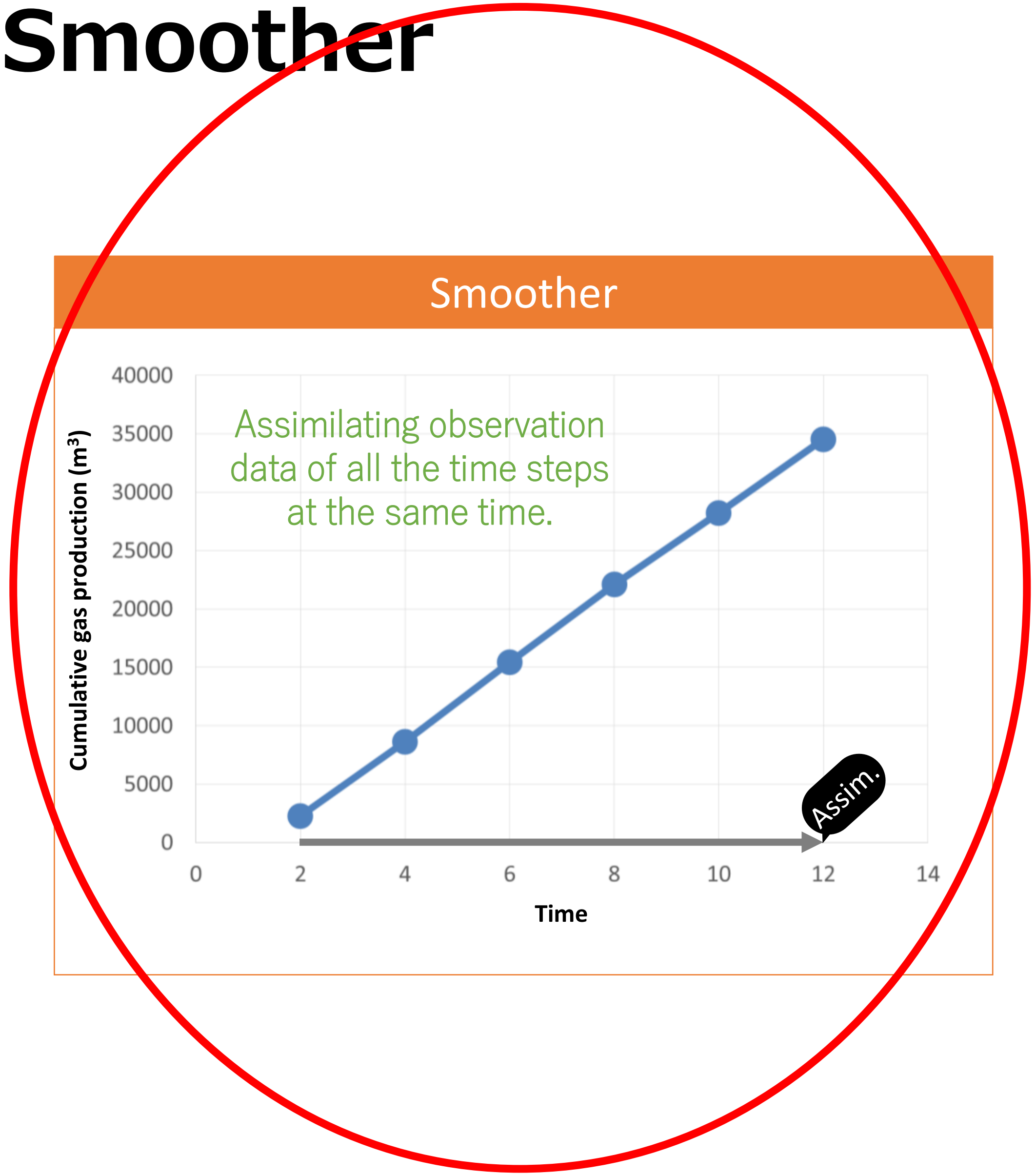
References

- Methane hydrate studies and offshore production test in the eastern Nankai Trough
  - Yamamoto et al., 2019, DOI https://doi.org/10.1039/C9RA00755E
  - Ouchi et al., 2021, DOI https://doi.org/10.1021/acs.energyfuels.1c02931
  - Yamaoto et al., 2022, DOI https://doi.org/10.1021/acs.energyfuels.1c04119
- Japanese study results and models used
  - MH21 https://www.mh21japan.gr.jp/mh21wp/wp-content/uploads/phase2_3_5_1_1e.pdf
- Alaska long-term production test
  - Boswell, 2022, https://doi.org/10.1021/acs.energyfuels.1c04087

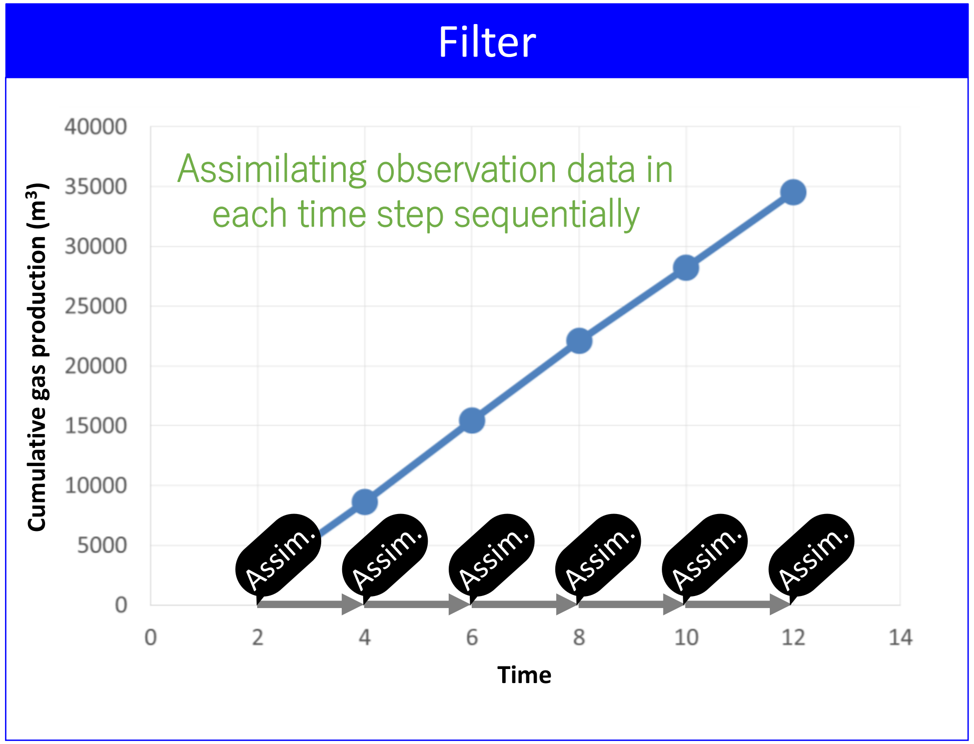
Appendix

Data Assimilation Algorithm (1/3)
Filter vs. Smoother





Data Assimilation Algorithm (2/3)
Filter

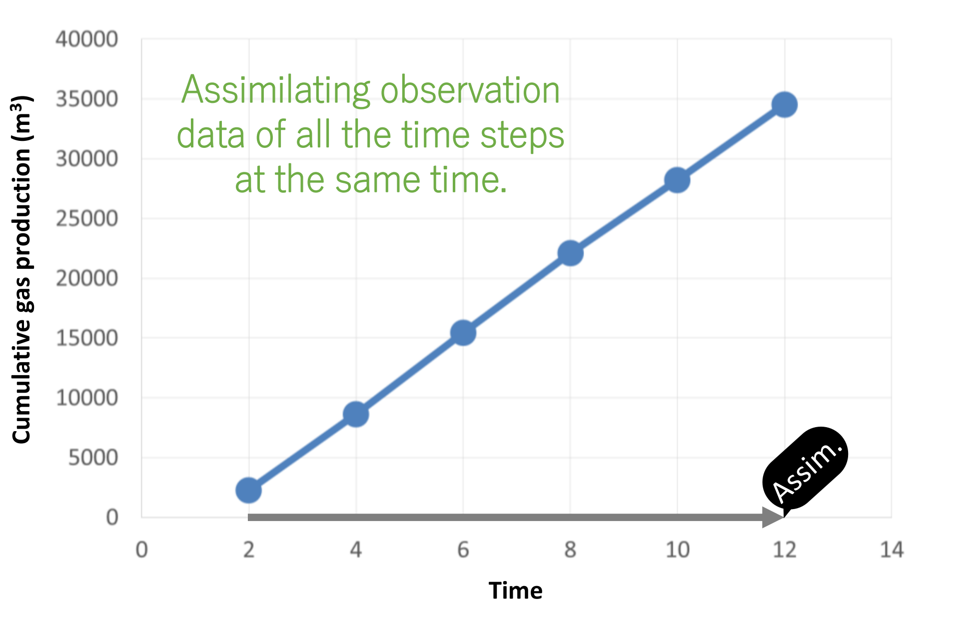


- Allow to modify physical parameters discontinuously
  - ➡ Considered to be suitable for highly nonlinear system
- However, discontinuous physical parameter changes caused by DA could lead to catastrophic calculation instability in MH simulations   Why?
  - ➡ Difficult to recover reservoir material balance if fluids were excessively produced from the reservoir in the past time steps.

Seems to be difficult to apply to MH simulations

Data Assimilation Algorithm (3/3) Smoother

Smoother

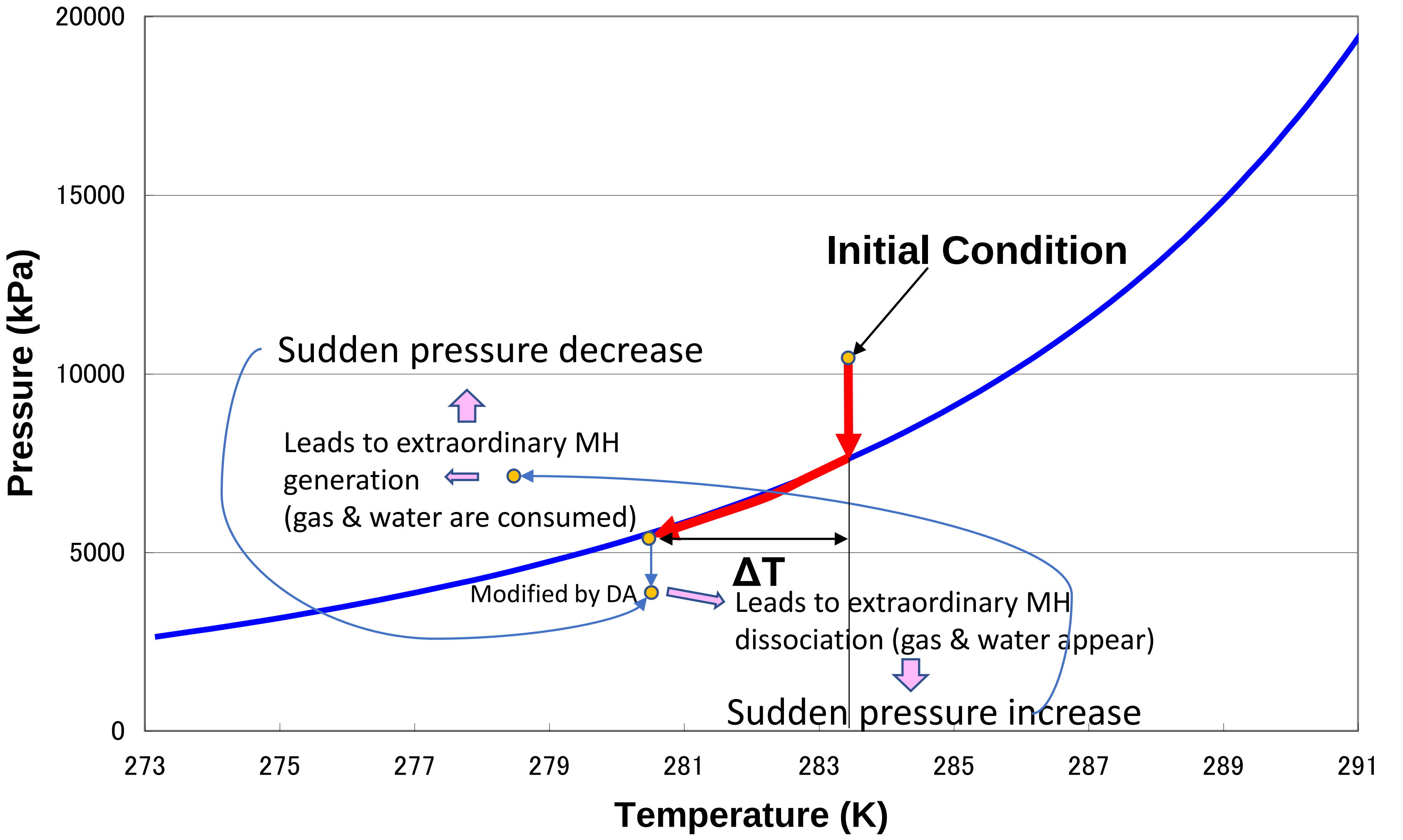


- Modifying parameters at the initial condition so as to match observation data of all the time steps
  - ⇒ Relatively difficult to follow sudden physical condition changes than filter
- However, calculation instabilities caused by discontinuous physical parameter modification never happen.
- In addition, iteratively application of smoother method (such as iterative ES or ES-MDA) could improve the accuracy of DA.

Seems to be **more suitable** to the MH reservoir simulation than filter

⇒ Decided to use smoother types of DA algorithms in the preliminary test

Pressure Modification through DA in MH simulation



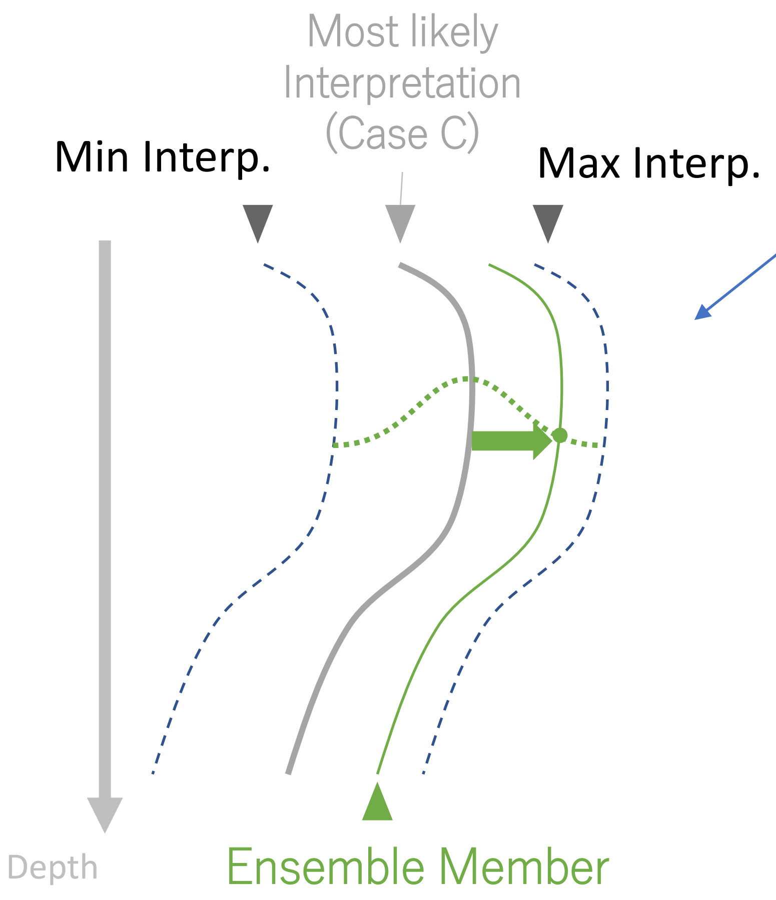
- Once MH dissociation begins, reservoir pressure and temperature move along with the three phase equilibrium curve toward the low temperature direction.
- At that time, pressure and temperature keep very slightly lower position of the three phase equilibrium curve.
- However, if pressure is modified through the data assimilation process regardless of equilibrium condition, calculation becomes unstable due to the following procedure.

$$\dot{m}_h = cA_h\left(p_{eq} - p\right)$$

- Therefore, pressure cannot be modified in data assimilation in MH simulations.

Return

Generation of Initial Ensemble Members



There are three different well-log interpretations (min, max, and most likely) in the target reservoir.

Each ensemble member is generated by interpolating the two different well logs by using random value between -1 and 1

① Generating random value between -1 and 1

② Interpolating the two different well-log interpretations (most likely- min or most likely – max) based on the random value

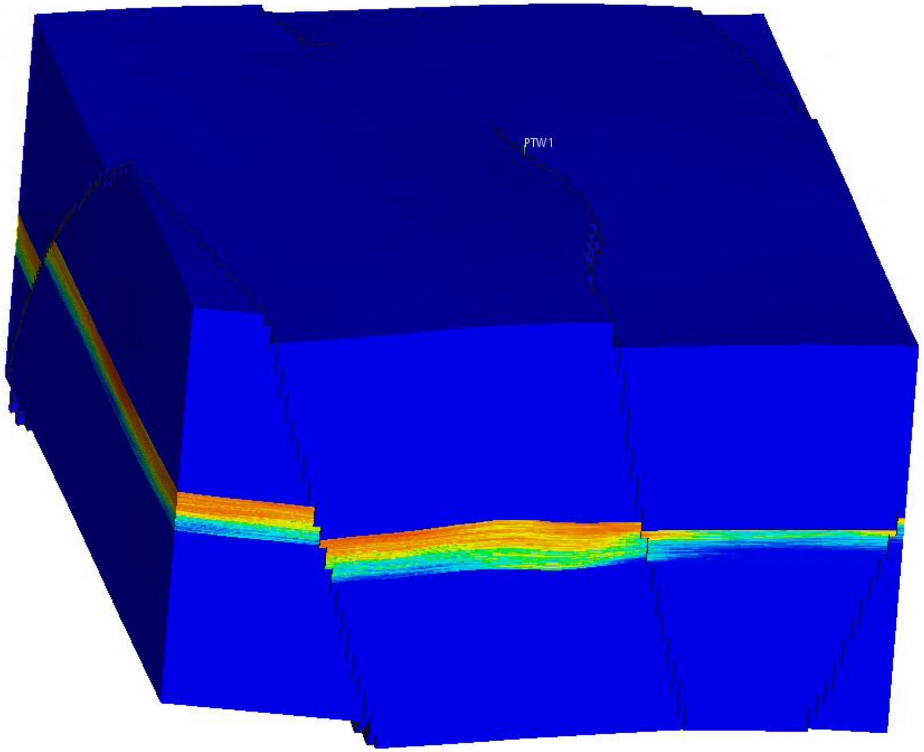
return

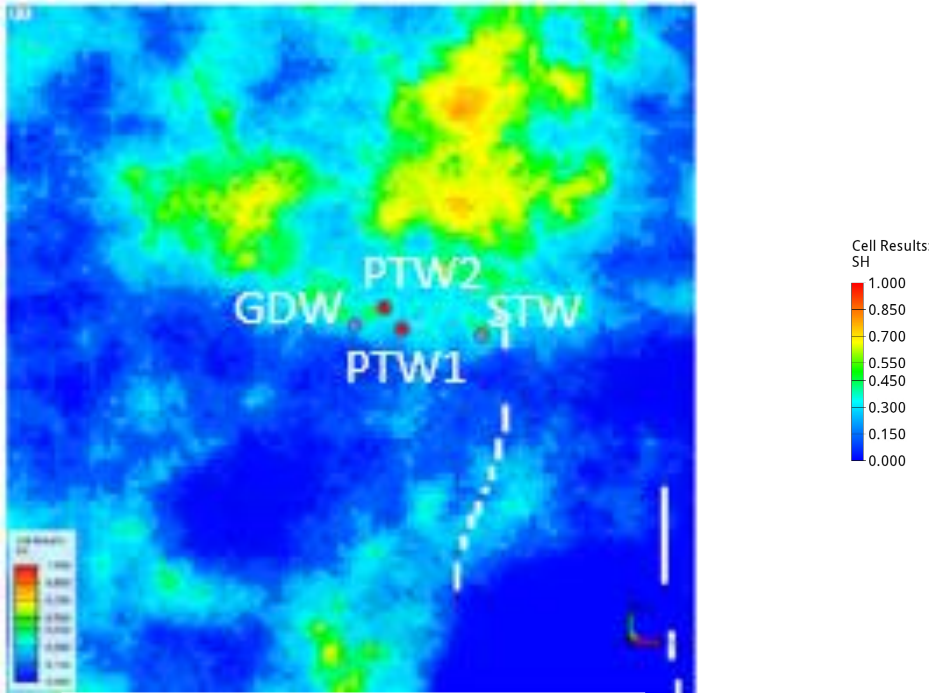
Case2B: Reference Model

3D Heterogeneous Model

MH Saturation ： Laterally Heterogeneous
Abs. Perm & N : Laterally Homogeneous

Initial Effective Permeability: Laterally Heterogeneous

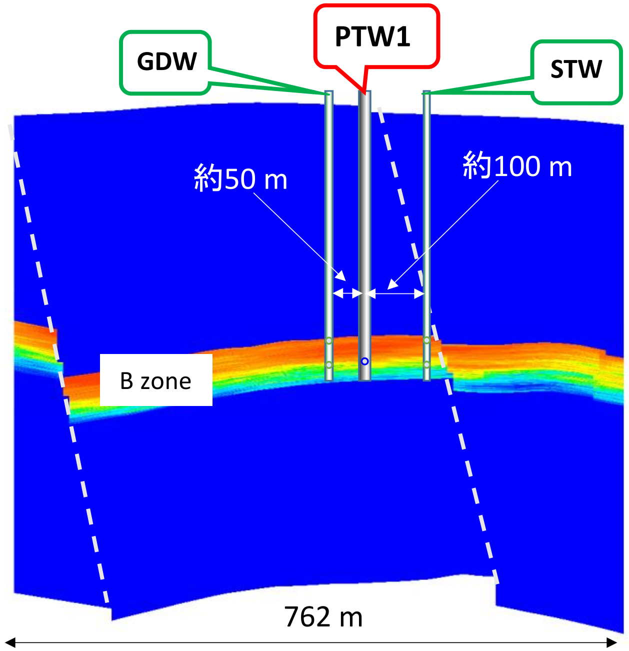




Initial MH Saturation (K= 195 Layer)

Case 2B Data Assimilation Settings

☐ Observation Data for DA, and Data Acquisition Timing

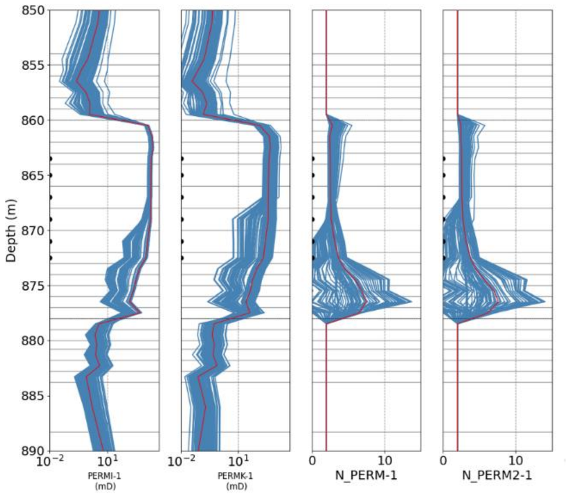


- **PTW1:** Cumulative Gas/Water Prod.
- **GDW:** Pressure/Temperature

STW data was not included in this Case

☐ Data Acquisition Timing: every 30 days until 240 days

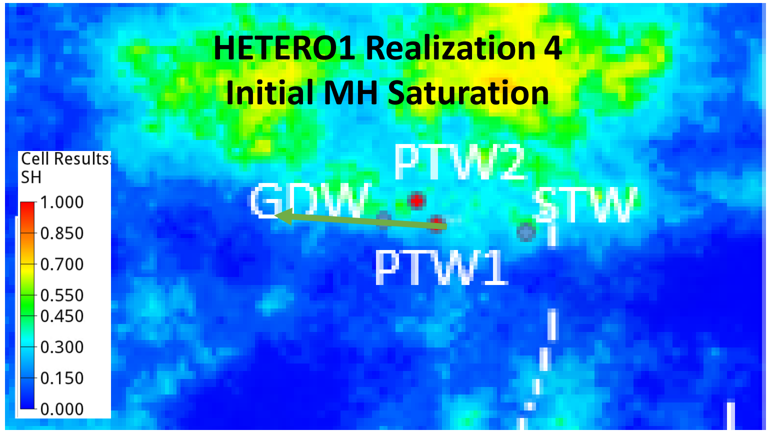
Initial Ensembles of the Estimated Parameters (permeability, permeability reduction index, MH Saturation)

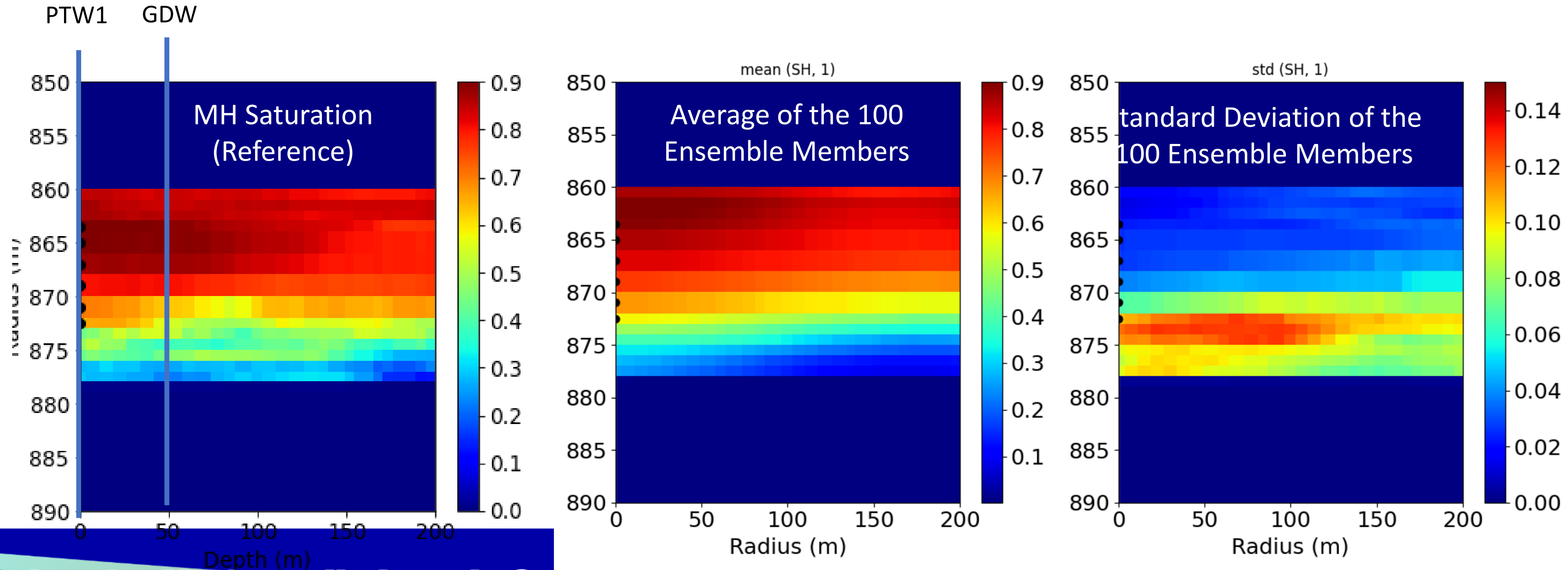


- Horizontal Absolute Permeability (k_{absH})
- Vertical Absolute Permeability (k_{absV})
- Horizontal Permeability Reduction Index (N_H)
- Vertical Permeability Reduction Index (N_V)
- MH Saturation (Sh)

Generation of the Initial Ensemble (MH Saturation)

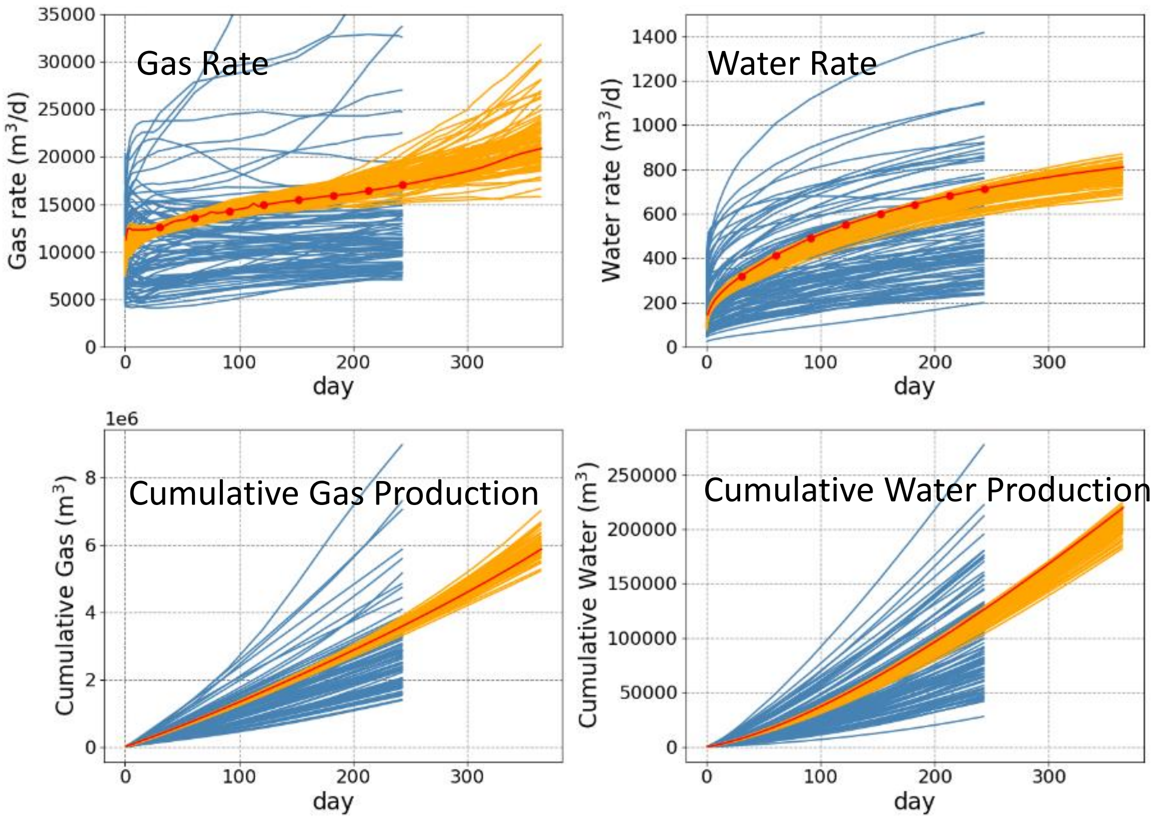
- Extracting MH saturation from the 100 realizations of the 3D Model along with the line between PTW1 and GDW
- Generating ensemble of MH saturation by Interpolating the extracted value so as to match the cell frame in the 2D radial model



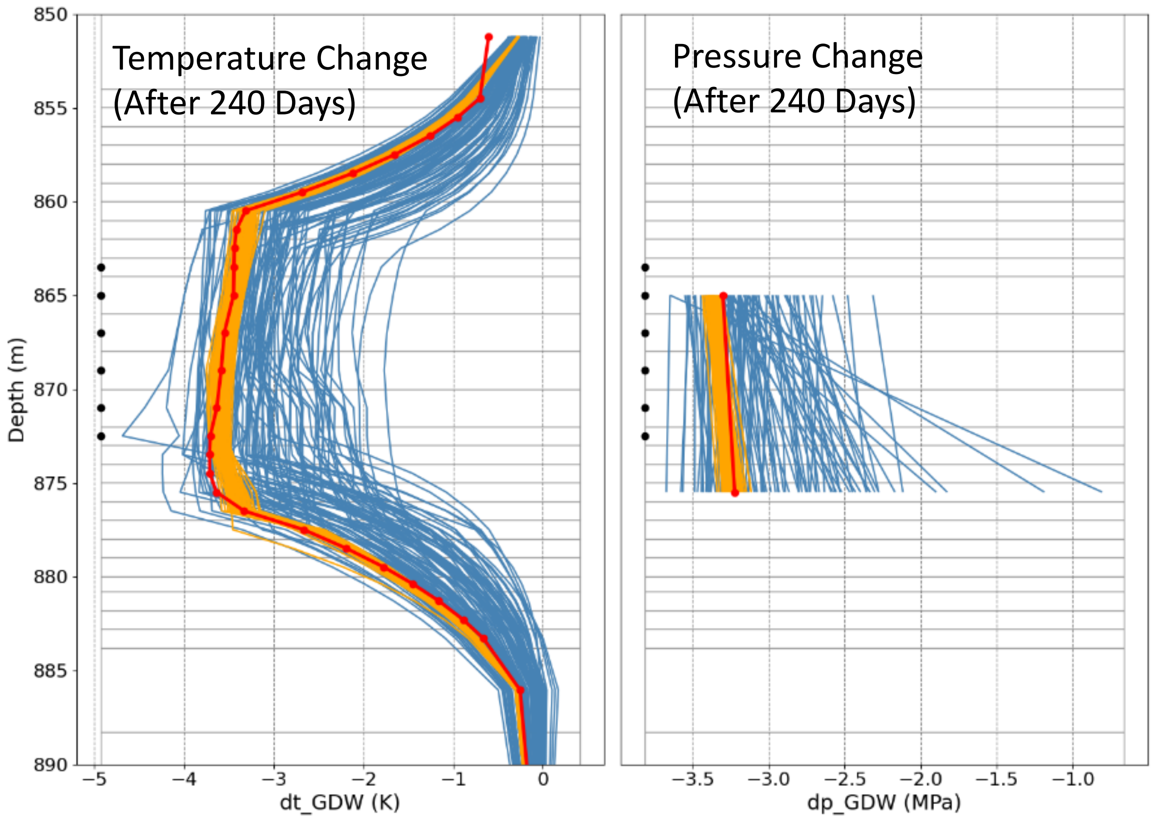


Case2B Results (Observation Data: PTW1 & GDW)

PTW1

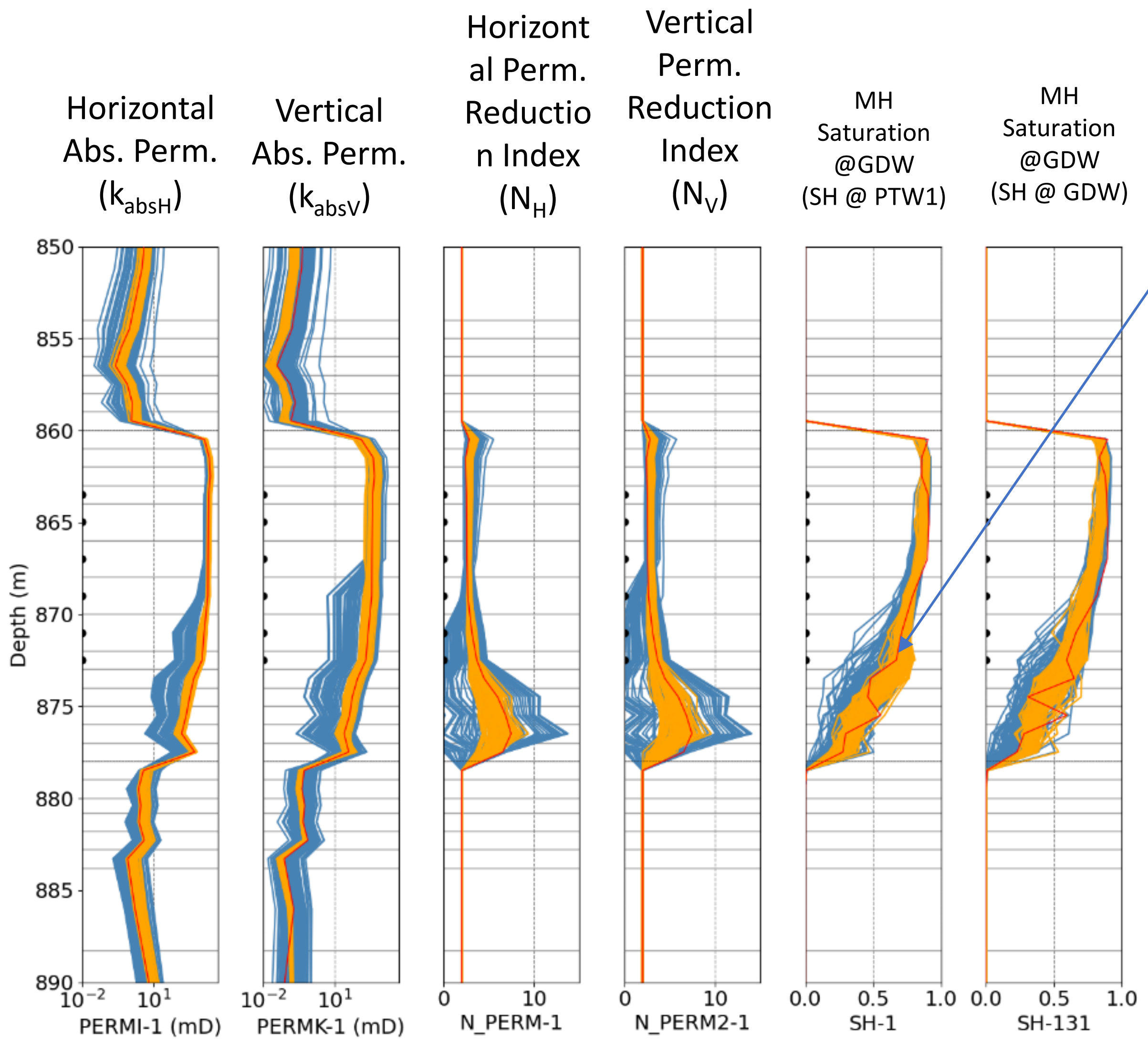


GDW



Blue Lines: Initial Ensemble Results
Orange Lines: Assimilation Results
Red Lines: Reference Result

Case2B Results (Estimated Parameters)

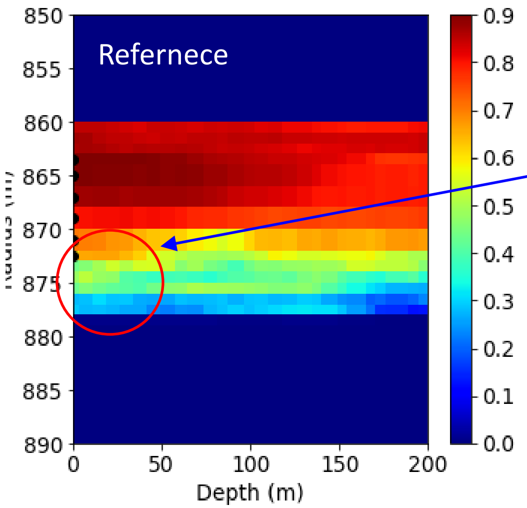


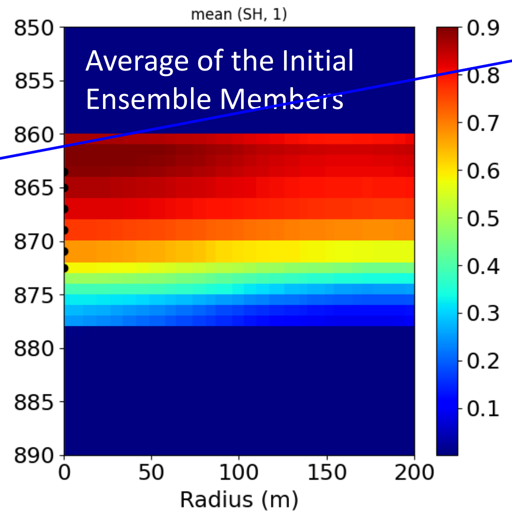
MH saturation is estimated well at least at the production well location.

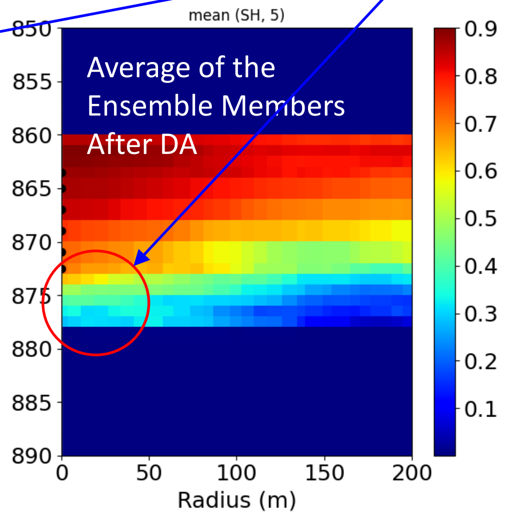
Blue Lines: Initial Ensemble
Orange Lines: Assimilation Results
Red Lines: Reference Result

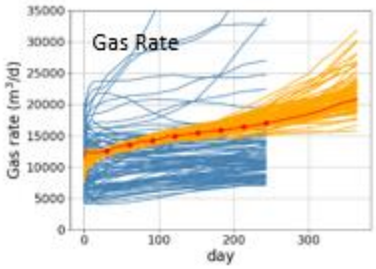
Case2B Results (Estimated MH Saturation)

Relatively high MH saturation trend at the reference model is well reproduced by DA.

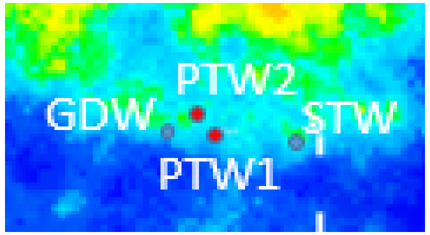


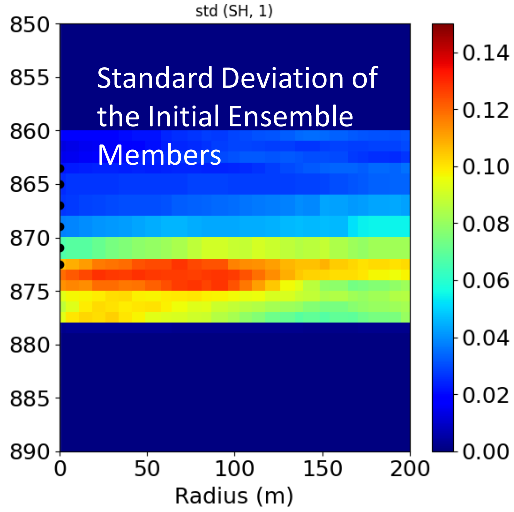


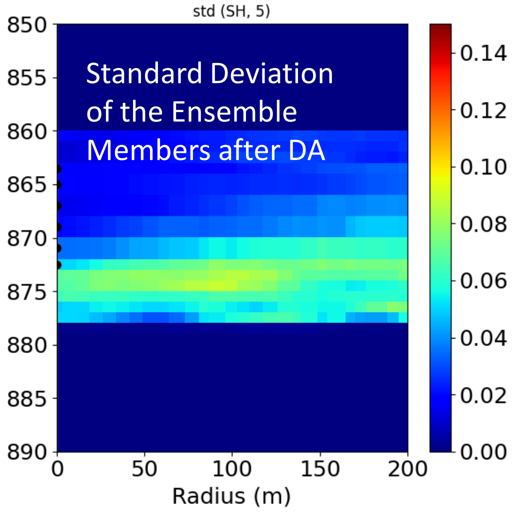




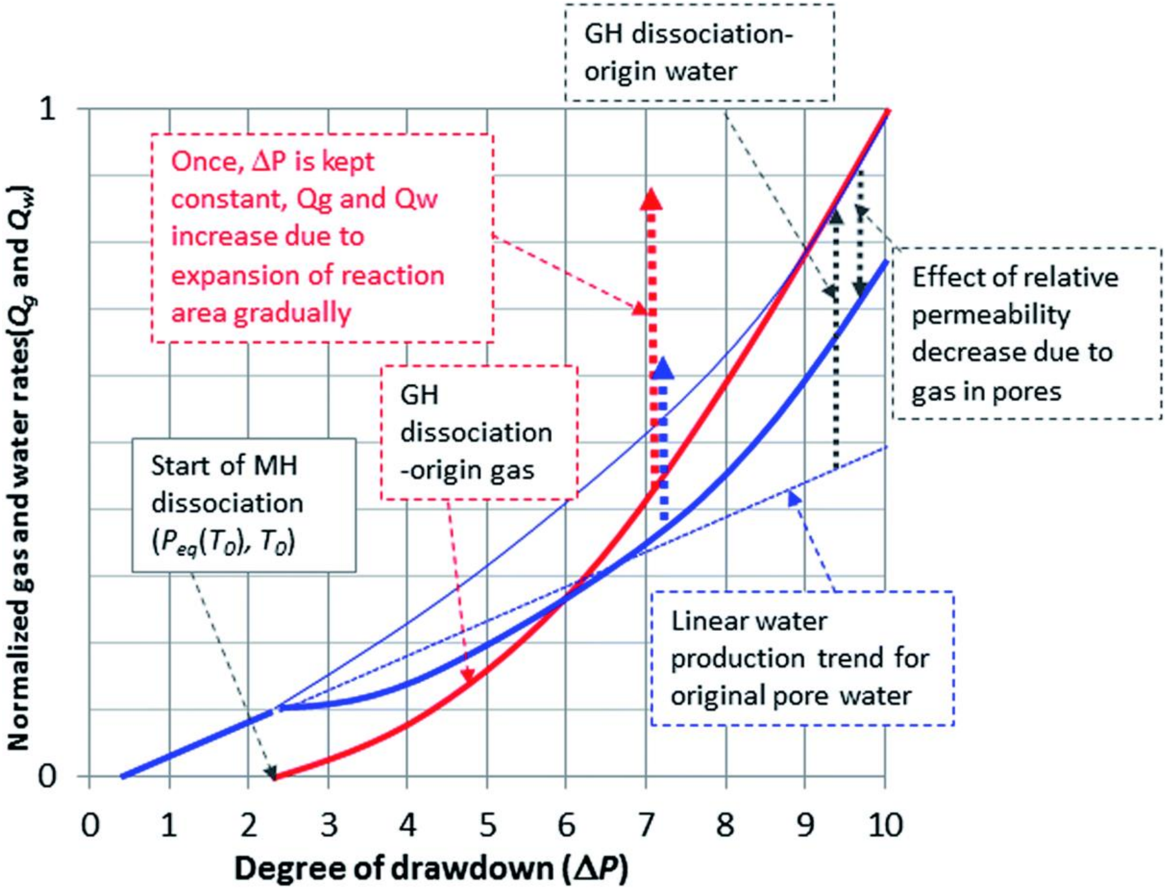
Hetero1 Realization 4

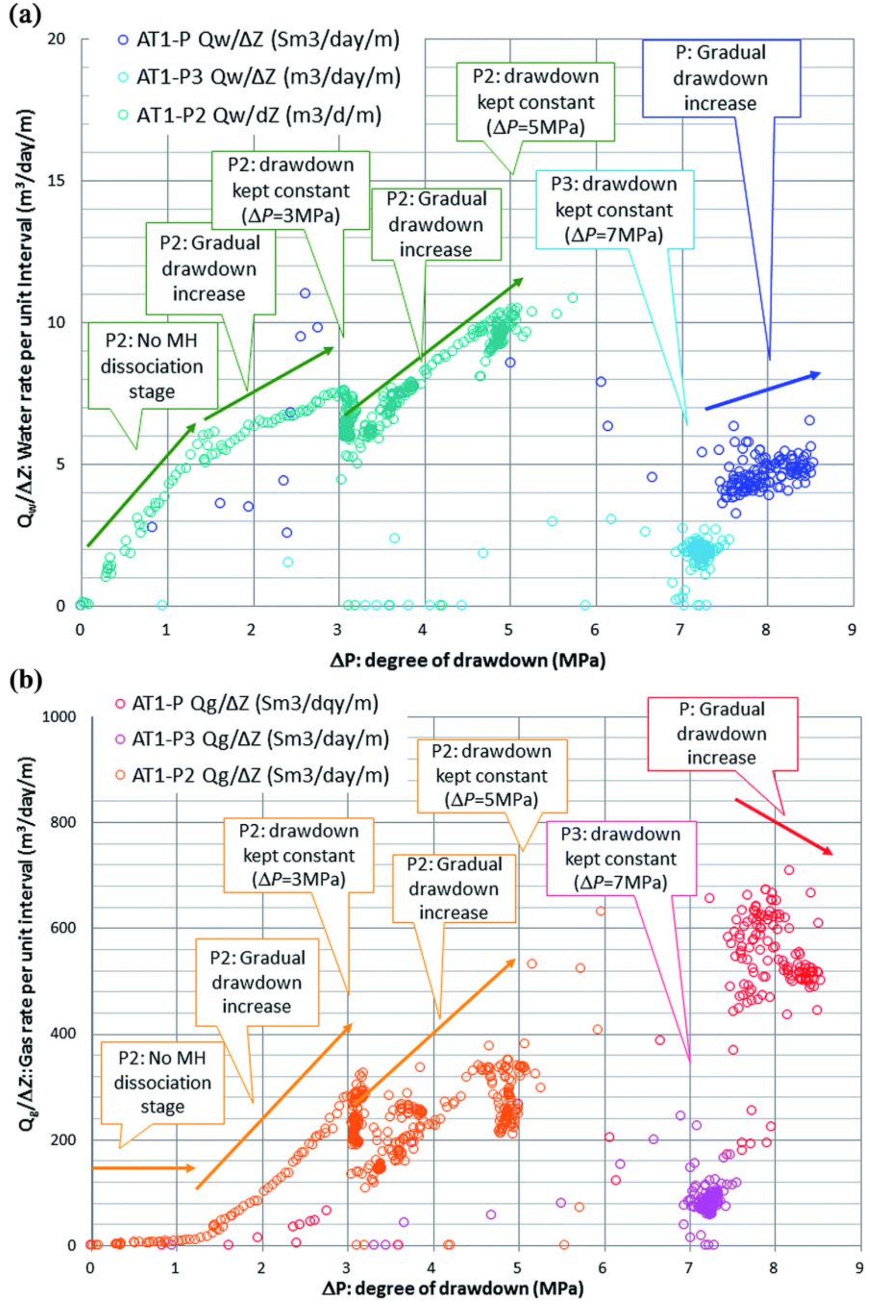






Examples: Difference between model expected and measured/monitored gas/water production and reservoir responses.





Theoretically expected vs. measure gas/water production rates with degree of drawdown

Yamamoto et al., 2019
DOI https://doi.org/10.1039/C9RA00755E